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A NUMERICAL STUDY IN OPTIMUM TRACK SHIP ROUTING CLIMATOLOGY

by

Frederick W. Nagle

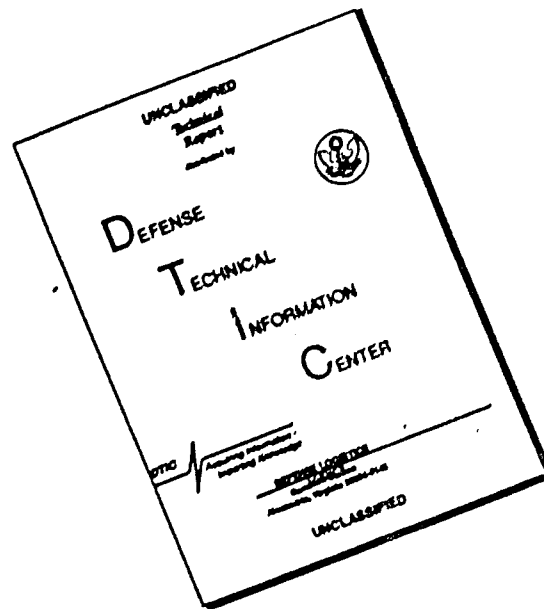
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A NUMERICAL STUDY IN
OPTIMUM TRACK SHIP ROUTING CLIMATOLOGY

by

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SEPTEMBER 1972

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ABSTRACT

A brief discussion of the background and history of optimum track ship routing is presented. The basic problems are formulated and the approach used in this investigation is described. The computing scheme is described graphically and textually.

The results of this investigation are presented in two forms: (1) computer-generated histograms showing mean time saved by month for various trans-Atlantic routes; and (2) computer-drawn charts of various routes, by class (described), plotted against 5-year surface and 500-mb means.

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1. INTRODUCTION

Although optimum track ship routing (OTSR) may be traced back to the work of Matthew F. Maury in the 19th century, its modern form has its origins in the work of Dr. Richard James of the Naval Oceanographic Office about 20 years ago. The digital computer being then in its infancy, the ideas advanced by James were necessarily based on manual and subjective techniques. Advances in computer technology in the meantime quite naturally encouraged investigators to adapt this tool to automated OTSR methods. An early and relatively primitive attempt along this line was undertaken by the Navy Weather Research Facility in the early 1960's (Nagle, 1961). Using more sophisticated mathematical techniques, further work in optimum route computation by digital computers was pursued by Haltiner, Bleick, Faulkner, and others at the Naval Postgraduate School, Monterey, California. In particular Bleick and Faulkner (1971) have summarized several of the methods used.

The task of optimum track ship routing may be divided into two sub-tasks:

- (1) The route forecaster must have available a reasonable estimate of sea conditions for a period of at least several days in advance, and preferably as long as two weeks. This does not imply that the existence and position of every storm must be accurately foreseen days in advance, but to be useful,

an optimum route forecast must be predicated on a substantially correct anticipation of at least major storm tracks, if not the actual storm centers themselves.

- (2) Given that the forecaster possesses some degree of skill in forecasting weather conditions over the oceans, the necessary mathematical tools must exist whereby the forecaster's knowledge can be objectively used to establish an optimum route.

It appears that significant progress has been made only in the second of these two sub-tasks, so that the major outstanding problems in OTSR today are meteorological, not mathematical. Indeed, mathematical precision has quite outstripped the reliability of meteorological inputs to the OTSR problem.

To digress for a moment, it is probably a misdirection of effort to achieve mathematical nicety in route forecasting when the lack of precision in forecasting weather parameters is such that not even the grossest features of an optimum route can be reliably predicted. For example, incidents have occurred wherein the route forecaster's chief dilemma was whether to send a westbound vessel departing a German port westward through the English Channel, or "over the top" north of the British Isles. In such a situation, the forecaster might have thought himself well served if a computer program could have dependably suggested one or the other of these two

alternatives as the better, all other features of the optimum route being thereafter considered relatively minor.

A variation on this theme is found in the case of a forecaster who is prepared to recommend any one of a small number of standard, frequently-used routes, and requires only a good estimate of which is best. If accurate, long-range forecasts were available, the mathematics of choosing among a small number of "canned" routes is simple and perhaps almost trivial, yet the benefits to the maritime industry would be enormous. Some help may be found in a better phrasing of forecasts in the form of probabilities rather than in deterministic statements. Such forecasts might lead to the selection not of deterministic routes, but of probabilistic routes offering the least-time expectation of a voyage. These would be based upon knowledge which is attainable (i.e., probabilities), albeit with some difficulty, within the current state of the art.

2. FORMULATION

This paper addresses itself to two questions, which may be formulated as follows:

- (1) If it is assumed that high-quality sea-state forecasts are available for the North Atlantic for a period of about 10 days, how much time could a transiting vessel hope to save, averaged over many voyages, by making use of such forecasts for optimum route selection?
- (2) Do the mean surface and 500-mb maps, averaged over all such maps valid at the vessel's departure time for a large number of voyages, possess any characteristic features which offer guidance to a route forecaster as to the approximate nature of the optimum route?

The following approach was used to investigate these questions: Sea-state maps depicting wave height and direction and valid at 12-hour intervals over a 5-year period were obtained from Fleet Numerical Weather Central, Monterey, California. This provided a total of approximately 3500 consecutive maps, with only a few maps missing. Two types of hypothetical ships were chosen for this study as well as two eastbound and two westbound trans-Atlantic voyages. One of the ships was chosen to represent a small, slow cargo vessel with a speed of about 15 knots, and the other a larger passenger ship of about 20 knots. (The characteristics of these

ships were actually chosen to represent a C-2 cargo vessel, and a P-2 passenger ship, using information obtained from James (1957).) The four routes were east- and westbound between Norfolk and Gibraltar, and between Norfolk and Bishop Rock, at the western end of the English Channel. The available maps covered the period from January 1966 to November 1970. The only parameters allowed to influence the speed of a ship being routed were wave height and wave direction relative to the ship. Wave period was not considered, nor were other variables such as fog, ice, traffic, or operational factors. A computer program was then written in Fortran IV for the Univac 1107 computer to initiate a routing every 12 hours throughout the 5-year period. The program selected the optimum route by a technique to be described, and computed the time to transit via both the optimum and a pre-selected standard route such as a Great Circle or other arbitrarily chosen path. The term "Optimum" is used here in the sense of "least-time" rather than "least-cost". The computer time required to compute a least-time track, and its associated standard-time crossing, averaged about 15 seconds. Computation time was closer to 20 seconds on voyages encountering heavy weather, and about 12 seconds on the summer "moonlight cruises", in the case of the 15-knot ship. The 20-knot ship required somewhat less time per voyage. The Univac 1107 is a 1962-vintage computer and is about one-fifth as fast as the Univac 1108. Two magnetic tapes were required while the

program was running; one to contain the input sea-state data, and the other an output tape to record the results of each voyage. It was this output tape which was later processed by other programs to obtain statistical route information.

The Univac 1107 possesses a 65K memory, of which only 53K is available to the user after allowance is made for the resident executive routines. This memory was easily adequate for the Atlantic program, and no use was made of the available drum memory.

A program similar to the Atlantic OTSR model was written for the Pacific, and was actually run on a limited basis. Indeed, optimum routing in the Pacific is perhaps more challenging than in the Atlantic, both operationally and meteorologically, and the original hope had been to make an extensive Pacific study. With the Pacific model, however, the core memory was not adequate to contain the needed arrays, partly because the sea-state arrays are larger for the Pacific than for the Atlantic, and partly because more of them must be simultaneously stored due to the greater duration of trans-Pacific voyages. This fact demanded the use of drum memory. Regretably, the drum memory handling routines were never fully debugged, resulting in loss of certain routes during periods of very stormy weather. In view of the then-pending disestablishment of NWRF in June 1971, it was necessary to make a decision either to take time debugging the Pacific

model, or to proceed with the Atlantic study for which a debugged program already existed. The latter course was chosen.

In order to estimate the speed of a ship in a given sea condition, the program used an empirical function expressing speed in knots as a function of wave height and wave direction relative to the ship's heading. In the rare event that the speed thus calculated was less than one knot, an arbitrary speed of one knot was used to simulate the ship in a hove-to condition. The original function was based on speed vs sea-state data obtained many years ago by James (1957), and should not be regarded as truly representative of any ship. The results of these approximations are shown in Figures 1 and 2 for the 15-knot and 20-knot vessel, respectively.

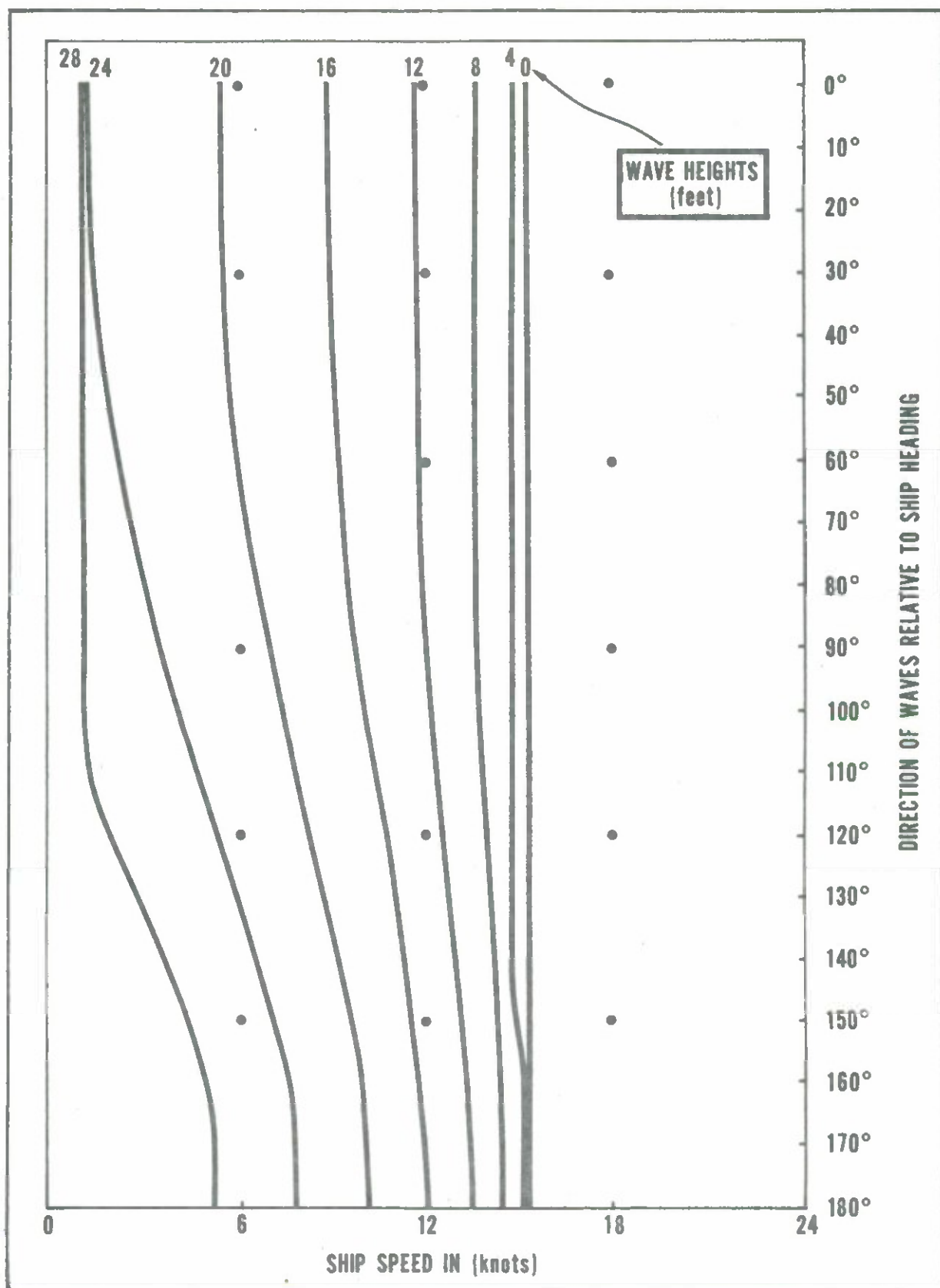


Figure 1. Ship speed as a function of wave height and wave direction relative to ship's heading (15-knot ship).

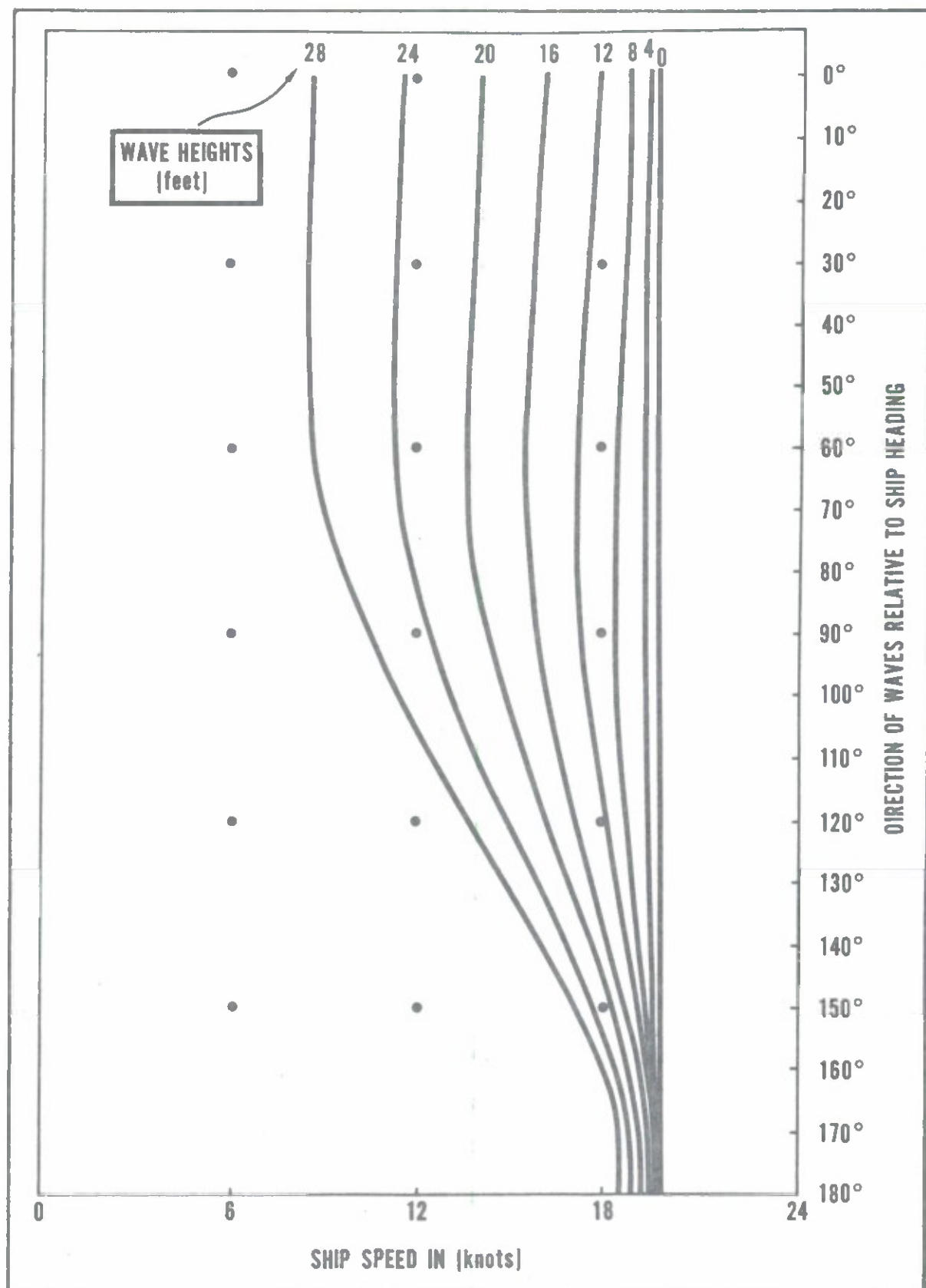


Figure 2. Ship speed as a function of wave height and wave direction relative to ship's heading (20-knot ship).

3. COMPUTING SCHEME

The computing scheme may be portrayed using the diamond-shaped grid consisting of 61 points depicted in Figure 3, with a ship's point of departure at the left apex, and the destination at the right:

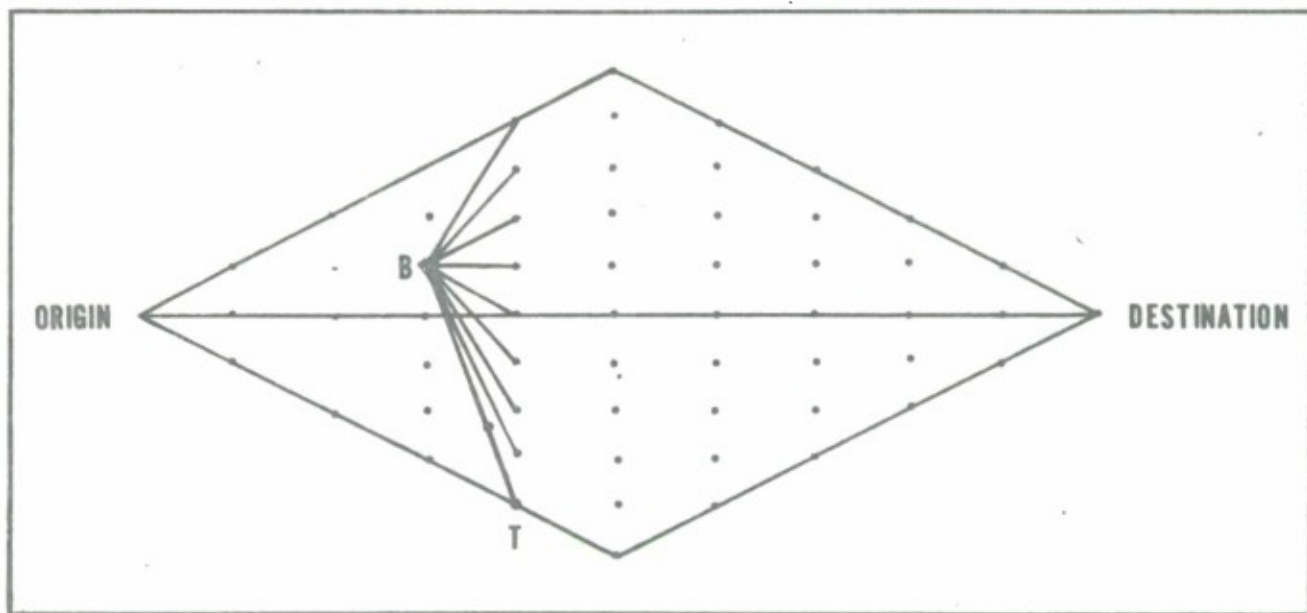


Figure 3. Optimum route computing scheme.

The number of points within this diamond grid, and certain features of its geometry, such as angular opening at each apex, are based partly on the size and speed of the computer, partly on experience, and to some degree are simply arbitrary.

In the course of computing an optimum route, the computer constrains the vessel to sail along the straight line segments emanating from a given point, such as B, toward all points in the next vertical column to the right. Hence, each of the rays emanating from B may ultimately be chosen as a

portion of the optimum route from origin to destination, provided of course that the optimum route passes through B.

The following definitions may now be offered:

- Node - Any one of the 61 points constituting the diamond grid
- Base Point - A node away from which a ship is sailing at a given instant
- Target - A node toward which a ship is sailing at a given instant
- Optimum - A path passing through exactly one node in each vertical column which minimizes the time required to sail from origin to destination.

Using the foregoing definitions, it may be said that with respect to a ship instantaneously at point P, its base point is B, and its target is T.

One of the arrays in the program is a 61-word array which, for each node, records the Actual Time of Arrival (ATA) at that node. The value of ATA is not unique, since it is a function of the path from the origin to the node, and of the sea conditions along the path. At the outset of the run, the value zero is entered for ATA at the origin, and a very large positive number ("positive infinity") is pre-stored at the remaining 60 points of the ATA array.

For easier viewing, a portion of the diamond grid may be enlarged (see Figure 4). We assume for purposes of induction that the computer has somehow determined the Earliest Possible Time of Arrival (EPTA) at each node in the vertical column

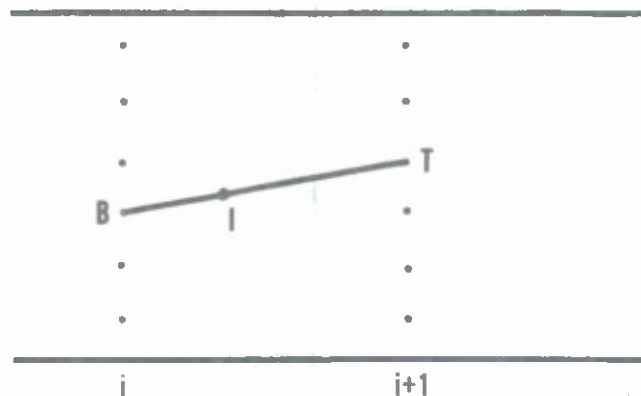


Figure 4. Enlarged portion of the diamond grid computing scheme.

labelled i . The object now is to find EPTA at each node in column $i+1$. Assume there is a ship at node B in column i proceeding toward node T in column $i+1$. The program estimates the speed at B, based upon hull type, sea conditions, and the direction of the waves relative to the heading of the ship. Using this estimate of speed, the ship is displaced for a time step of three hours, thereby placing the vessel at some intermediate point such as I. The speed is now recomputed based on sea conditions at I, and another 3-hour displacement is made, etc., until the vessel is within three hours of sailing to node T. The final ATA at node T is then computed, and compared with the value of ATA already stored for node T. This pre-existing value will be either the large positive quantity which was pre-stored during initialization, or will be an ATA resulting from a previously-computed track to node T. If the value of the newly-found

ATA is greater than the previous value, then the earlier value is left unchanged in the ATA array for the point $(i+1, j)$. But if the new ATA is smaller, then the old value is replaced by the new, and at the same time, an index value or identifier of the base point B is entered into a base point array (BP) to indicate that the node B is the point anterior to T along the path to T. This last step is necessary in order to allow the computer to later retrace the optimum route. This base point array (BP) is another 61-word array which, for each node T, contains the identifier of the node in the adjacent column to the left through which lies the optimum path to T.

The target node index is now incremented from j to $j+1$. The ATA at node $(i+1, j+1)$ is now found in a similar manner, either replacing or leaving any previously-found value of $ATA(i+1, j+1)$, and so on, for all target points in column $i+1$.

The next base point in column i is now used, and again all possible ATA's are found in column $i+1$. When all nodes in column i have been used as base points, the ATA values remaining for column $i+1$ will be the minimum values found for each ATA in column $i+1$. These minimum values are precisely the EPTA values for the $(i+1)^{th}$ column.

With the following notation, the foregoing discussion may be slightly formalized:

EPTA(i, j) - Earliest Possible Time of Arrival at the j^{th} node in column i .

TS(i,k,i+1,j) - Time needed to Sail from the kth node
in column i to the jth node in column
i+1.

Then:

$$EPTA(i,j) = \min_k (EPTA(i-1,k) + TS(i-1,k,i,j))$$

which may be regarded as the governing equation for the ship routing program.

The iteration process then proceeds from one column to another from left to right across Figure 3. The rightmost column consists of a single point, the destination, and when EPTA(11,1) has been found, the task is nearly complete. The optimum path is then reconstructed by observing for each node the anterior point through which the optimum path lies, by reference to the above-mentioned BP array.

Several points have thus far been overlooked. For example, during initialization of the program, the coordinates of the 61 points are computed and stored once and for all. The distribution of these nodes is primarily a function of the choice of origin and destination, although a certain amount of arbitrary distortion of the diamond grid can be introduced under program control so as to improve coverage of the ocean, avoid land masses, etc.

As the iteration proceeds, the program continually updates the current sea-state data by reading into memory a chronological sequence of sea-state maps obtained from Fleet Numerical Weather Central, Monterey. Special rules apply when some of

the data are missing. Normally, FLENUMWEACEN analyzes a sea-state map every 12 hours, so that a sea-state map can be found which is valid within 6 hours of any instant of time. The computer attempts to find maps from the map file valid within 6 hours, but if one or more maps is missing, then it attempts to find a map within 12 hours, then within 18, etc. If no map can be found which has a valid time within 24 hours of the instant at which it is needed the route is abandoned and a new voyage is initiated at the next time period following the hiatus in the data.

4. RESULTS

a. Histogram Presentation

The results written on the output tape by the optimum selection program were summarized in several ways, the simplest being a set of histograms printed by the computer displaying the time difference in hours required for transiting via the standard and selected optimum routes (see Figures 5 and 6). Ideally, this quantity represents the maximum amount of time that a vessel could hope to save if it were optimally-routed with the aid of sea-state forecasts which in accuracy were not worse than the sea-state analyses produced by Fleet Numerical Weather Central as an operational product. This potential saving is categorized by month on the histograms.

The computer subroutine which drew the histograms was such that the longest bar on each graph was 100 print positions in length, and all shorter ones normalized to this length. Hence, bars of equal length do not represent the same number of hours from one histogram to the next. The actual numeric value associated with each bar of a histogram appears at the right in exponential format, so that $.132+2$ means 13.2, for example.

The first histogram, Figure 5a shows the potential time saved in hours on the run from Bishop Rock to Norfolk. The general distribution of time saved is about what one might intuitively expect, i.e., a winter maximum and summer minimum,

MEAN TIME SAVED BY MONTH											
15-KNOT VESSEL, BISHOP ROCK TO NORFOLK											
JAN	+	+	+	+	+	+	+	+	+	+	.129+02
FEB	+	+	+	+	+	+	+	+	+	+	.164+02
MAR	+	+	+	+	+	+	+	+	+	+	.031+01
APR	+	+	+	+	+	+	+	+	+	+	.032+01
MAY	+	+	+	+	+	+	+	+	+	+	.510+01
JUN	+	+	+	+	+	+	+	+	+	+	.183+01
JUL	+	+	+	+	+	+	+	+	+	+	.142+01
AUG	+	+	+	+	+	+	+	+	+	+	.217+01
SEP	+	+	+	+	+	+	+	+	+	+	.425+01
OCT	+	+	+	+	+	+	+	+	+	+	.498+01
NOV	+	+	+	+	+	+	+	+	+	+	.573+01
DEC	+	+	+	+	+	+	+	+	+	+	.758+01

Figure 5(a). Potential time saved, by month, 15-knot vessel, Bishop Rock to Norfolk.

U.S.-K. JOI VESSEL. CHINA: IAR TO HOKKAI

JUN	.131+07
MAY	.186+02
MAR	.979+01
APR	.035+01
MAY	.034+01
JULY	.178-00
JUL	.333-00
AUG	.523-00
SEPT	.236+01
OCTO	.563+01
NOV	.419+01
DEC	.719+01

Figure 5(b). Potential time saved, by month, 15-knot vessel, Gibraltar to Norfolk.

WORTHINGTON TO BILLY'S ROCK • 15-KNOT VESSEL

JAN	.96+01
FEB	.91+01
MAR	.46+01
APR	.52+01
MAY	.28+01
JUN	.13+01
JUL	.13+01
AUG	.14+01
SEP	.73+01
OCT	.39+01
NOV	.54+01
DEC	.41+01

Figure 5(c). Potential time saved, by month, 15-knot vessel, Norfolk to Bishop Rock.

MEAN TIME SAVED BY MONTH											
15-KNOT VESSEL, NORFOLK TO GIBRALTAR											
JAN	+	+	+	+	+	+	+	+	+	+	.677+01
FEB	+	+	+	+	+	+	+	+	+	+	.639+01
MAR	+	+	+	+	+	+	+	+	+	+	.254+01
APR	+	+	+	+	+	+	+	+	+	+	.411+01
MAY	+	+	+	+	+	+	+	+	+	+	.896-00
JUN	+	+	+	+	+	+	+	+	+	+	.945-01
JUL	+	+	+	+	+	+	+	+	+	+	.107+00
AUG	+	+	+	+	+	+	+	+	+	+	.195-00
SEP	+	+	+	+	+	+	+	+	+	+	.191+01
OCT	+	+	+	+	+	+	+	+	+	+	.465+01
NOV	+	+	+	+	+	+	+	+	+	+	.350+01
DEC	+	+	+	+	+	+	+	+	+	+	.265+01

Figure 5(d). Potential time saved, by month, 15-knot vessel, Norfolk to Gibraltar.

although a secondary minimum in March was not anticipated, and the reason for it can only be guessed. Although there is always the possibility that this March minimum has climatic significance, it is also known that March 1968 was an especially stormy month, and the computer may have been compelled on many occasions during that month to choose among a number of poor routes, no route being really favorable. Hence, opportunities to save time by a shrewd choice of route would have thus been minimized.

The number of routings occurring in each month during the 5-year period averaged about 280, the fewest being about 240 for the four Decembers 1966-1969, and the largest number being 311 for the five Januaries 1966-1970. This distribution holds approximately for the other histograms as well.

The remaining three histograms of Figure 5 display the potential time saved for Gibraltar-to-Norfolk, Norfolk-to-Bishop Rock, and Norfolk-to-Gibraltar, respectively. The secondary minimum in March is a persistent feature on the Gibraltar runs as well as on the more northerly Bishop Rock runs. The greatest potential saving appears on the west-bound Bishop Rock to Norfolk run in February, being 16.4 hours. The smallest saving occurs in June on the eastbound Norfolk to Gibraltar run, being .0945 hours, i.e., less than six minutes as the average potential saving per voyage. The standard route used for the voyages between Norfolk and Gibraltar was the Great Circle, and during the summer months

the computer usually chose this path as optimum, resulting in no saving of time.

It will be seen that in all cases, the monthly average of time saved was greater on the westbound routes than on the corresponding eastbound routes. These figures suggest that the routing of westbound ships may be of greater value than eastbound, presumably because eastbound ships are more likely to encounter following seas and hence more favorable sailing conditions. The hourly cost of operating a ship is not known to the author, and in any case might vary greatly depending on one's method of accounting. It is readily seen, however, that the potential for reducing the cost of a voyage can be quite great on a westbound track during the winter months. The summertime minimum on both east- and westbound voyages between Norfolk and Bishop Rock is greater than on the Gibraltar runs because the Great Circle was not chosen as the standard route on the Bishop Rock voyages. Thus, it was easier for the computer to find a route better than the standard route.

A similar set of histograms is given in Figures 6a through 6c for the larger and faster 20-knot vessel, except that the Norfolk to Bishop Rock histogram is not available. The larger ship, being less adversely affected by high seas, offers less opportunity for saving time by optimum routing. The greatest saving is now only 5.56 hours on the westbound Bishop Rock-to-Norfolk voyages in January. On eastbound

MEAN TIME SAVED BY MONTH	
20-KNOT VESSEL, BISHOP ROCK TO NORFOLK	
JAN	.456+01
FEB	.495+01
MAR	.292+01
APR	.386+01
MAY	.261+01
JUN	.176+01
JUL	.172+01
AUG	.188+01
SEP	.195+01
OCT	.262+01
NOV	.229+01
DEC	.258+01

Figure 6(a). Potential time saved, by month, 20-knot vessel, Bishop Rock to Norfolk.

MEAN TIME SAVED BY MONTH											
20-KNOT VESSEL, GIBRALTAR TO NORFOLK											
JAN	+	+	+	+	+	+	+	+	+	+	.741+01
FEB	+	+	+	+	+	+	+	+	+	+	.187+01
MAR	+	+	+	+	+	+	+	+	+	+	.724-00
APR	+	+	+	+	+	+	+	+	+	+	.115+01
MAY	+	+	+	+	+	+	+	+	+	+	.214-00
JUN	+	+	+	+	+	+	+	+	+	+	.201-01
JUL	+	+	+	+	+	+	+	+	+	+	.144-01
AUG	+	+	+	+	+	+	+	+	+	+	.288-01
SEP	+	+	+	+	+	+	+	+	+	+	.210-00
OCT	+	+	+	+	+	+	+	+	+	+	.687-00
NOV	+	+	+	+	+	+	+	+	+	+	.789-00
DEC	+	+	+	+	+	+	+	+	+	+	.997-00

Figure 6(b). Potential time saved, by month, 20-knot vessel, Gibraltar to Norfolk.

20-KNOT VESSEL, NORFOLK TO GIBRALTAR

Figure 6(c). Potential time saved, by month, 20-knot vessel, Norfolk to Gibraltar.

voyages to Gibraltar, the graphs indicate that it is almost impossible to improve on the Great Circle as an optimum path.

b. Chart Presentation

A second type of output is displayed in the form of surface and 500-mb charts. These are categorized by route class, a term which is now defined (see Figure 7).

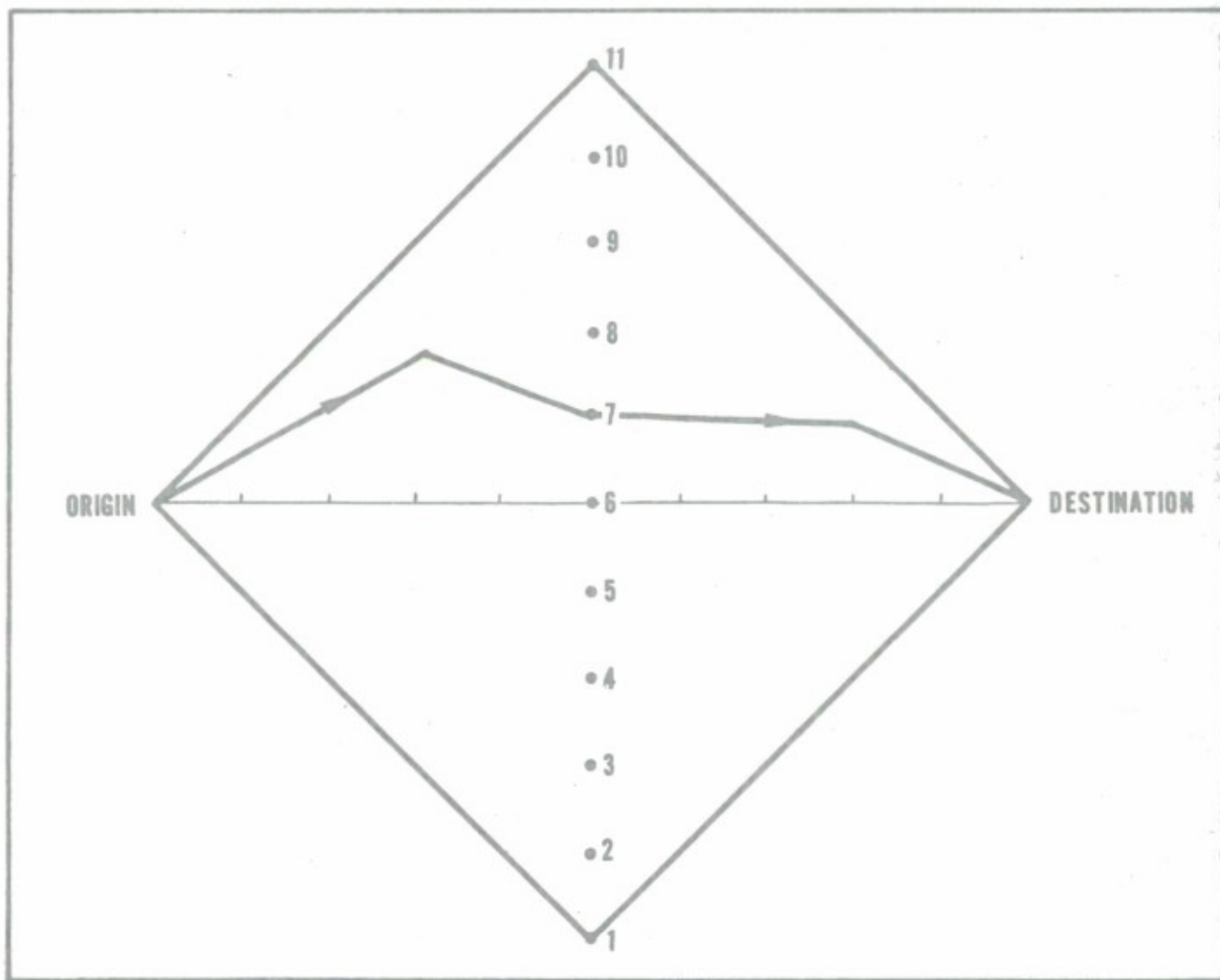


Figure 7. Schematic description of route classes.

The nodes in the center column of points joining the upper and lower apices of the diamond grid are numbered 1 to 11. All routes passing through the node labelled 1 are said to belong to Class 1, those passing through node 2 to Class 2, etc., and those passing through node 11 to Class 11. The output tapes produced by the optimum routing program were processed in a manner which selected all voyages in a given class, noting the dates on which such voyages were begun. From a separate file of 12-hourly surface and 500-mb charts valid at the departure times, the computer chose and averaged a sequence of charts so as to produce composite surface and upper air charts, one for each class of route. Note that for the eastbound routes, Class 1 voyages are the southernmost and Class 11 the most northerly, whereas for westbound voyages, the diamond grid would be viewed upside down, so that Class 1 voyages are the most northerly.

A total of 122 maps generated by the program are reproduced and presented in the appendixes to this paper. The maps display not only the averaged isobars and contours, but also the diamond grid used for a particular origin-destination pair. The mean path, representing the average of all voyages of a given class, is also drawn. The twelve numerals inscribed along the bottom just above the caption indicate the number of voyages occurring in each month over the 5-year period, so as to depict the seasonal distribution of the voyages making up the composite. These maps were all drawn off-line by digital

plotting equipment using a control tape created by the computer as part of the summarization program.

Appendix A depicts mean surface and 500-mb charts for the westbound Bishop Rock to Norfolk runs for a 15-knot vessel. The most northerly routes chosen by the computer, six voyages in all, belong to Class 4, all in winter (Figure A-1). The mean surface map is characterized by an intense trough extending across the North Atlantic at about 55° North. A supporting trough appears also at 500 mb, accompanied by an intense jet off the east coast of North America. Since only six cases are included in this composite, pronounced features are not averaged out as in other classes containing a large number of constituent maps.

With increasing class number (i.e., increasingly southerly routes) the intensity both of surface and upper air features decreases abruptly. Whether this fact has climatic significance or represents merely the effect of averaging a large number of maps is not certain.

Class 6 (see Figure A-3), which includes the Great Circle, is a composite of 1253 maps, and possesses very weak gradients, the reason again being uncertain. There is, however, a fairly uniform distribution of Class 6 voyages throughout the year, with a slight preponderance in summer months.

The surface map for Class 7 (Figure A-4(a)) reveals a confused scramble of isobars over the southern U.S. and Atlantic.

The cause of this was not found before termination of the project, but is thought to be an error, possibly in computer timing, within the averaging routine.

Classes 8 through 11 (see Figures A-5 through A-8) show a deepening of the Iceland Low, again possibly an averaging phenomenon, and intensification of the upper air westerly gradient. It is readily noted that diversions in the selected route, either to the far south or far north, occur only in winter, while the more central routes are chosen in the remainder of the year, as might be expected.

Perhaps the most pronounced difference between Class 4 and Class 11, both winter situations, is in the fact that the trans-Atlantic Low in Class 4 is further south, suggesting that the computer, in the case of Class 4 routes, chose a path to place the vessel in following seas north of the low. It then took advantage of a relative lull between two low centers to bring the ship sharply southward toward Norfolk. Obviously nice timing is involved to steam southward between two low centers. With Class 11, the computer attempted no such artful timing, but merely elected to keep the vessel as far south as possible in order to escape strong head seas further north.

Appendixes B through D depict composite surface and 500-mb charts for other voyages (15-knot vessels), such as Norfolk to Bishop Rock, and for the east- and westbound routes between Norfolk and Gibraltar.

Appendixes E through G show similar maps computed and drawn for the hypothetical 20-knot ship. Some charts are missing due to the problem of confused isobars mentioned earlier, which was very severe in several cases.

Figures G-1 and G-2, though quite invalid, are shown to indicate one type of error present in the ship routing program. In order to keep vessels away from land masses and to simplify the program, grid points overlying land masses on the sea-state analyses were coded with the fictitious wave height of 31 feet. In the case of the small 15-knot vessel, this artifice served its purpose, since a 31-foot sea would appear to the machine to be a very severe impediment to navigation. With the larger ship, however, a 31-foot sea, though severe, is nevertheless navigable and is perhaps preferable to genuine high seas surrounding it, especially if the land mass lies along a geometrically favorable route (such as the Great Circle). In such a case, when stormy weather existed over the western Atlantic, the computer did not hesitate to send vessels across Newfoundland and Nova Scotia on certain west-bound tracks. Obviously, a more sophisticated strategem must be used to avoid land masses. This type of error did not occur on the Gibraltar routes, but only between Bishop Rock and Norfolk.

5. CONCLUSIONS

In general, the greatest potential time saving (against standard routes) appears on the westbound runs in winter, and the least on eastbound runs in summer. Larger, faster ships, being less adversely affected by high seas, offer less opportunity for saving time by optimum routing.

The advent of third and fourth generation computers, coupled with the existence of digital oceanographic data, afford marine meteorologists an opportunity to study optimum track ship routing climatology from both climatic and economic viewpoints. More sophisticated routing techniques, improved oceanographic data (both historical and synoptic), better modeling of ship behavior in given sea conditions, and the input of economic and operational factors should greatly enhance the ability to accomplish optimum track ship routing and the knowledge of its overall benefits.

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Bleick, W. E. and F. Faulkner, 1971: A survey of numerical ship routing. Proceedings of the Naval Oceanographic Conference, Naval Postgraduate School.

James, Richard W., 1957: Application of wave forecasts to marine navigation. U.S. Navy Hydrographic Offices, SP-1.

Nagle, F., 1961: Ship routing by numerical means. NWRP Technical Report 32-0361-042.

APPENDIX A

BISHOP ROCK TO NORFOLK

15-KNOT VESSEL

FIGURE A-1	Class 4
FIGURE A-2	Class 5
FIGURE A-3	Class 6
FIGURE A-4	Class 7
FIGURE A-5	Class 8
FIGURE A-6	Class 9
FIGURE A-7	Class 10
FIGURE A-8	Class 11

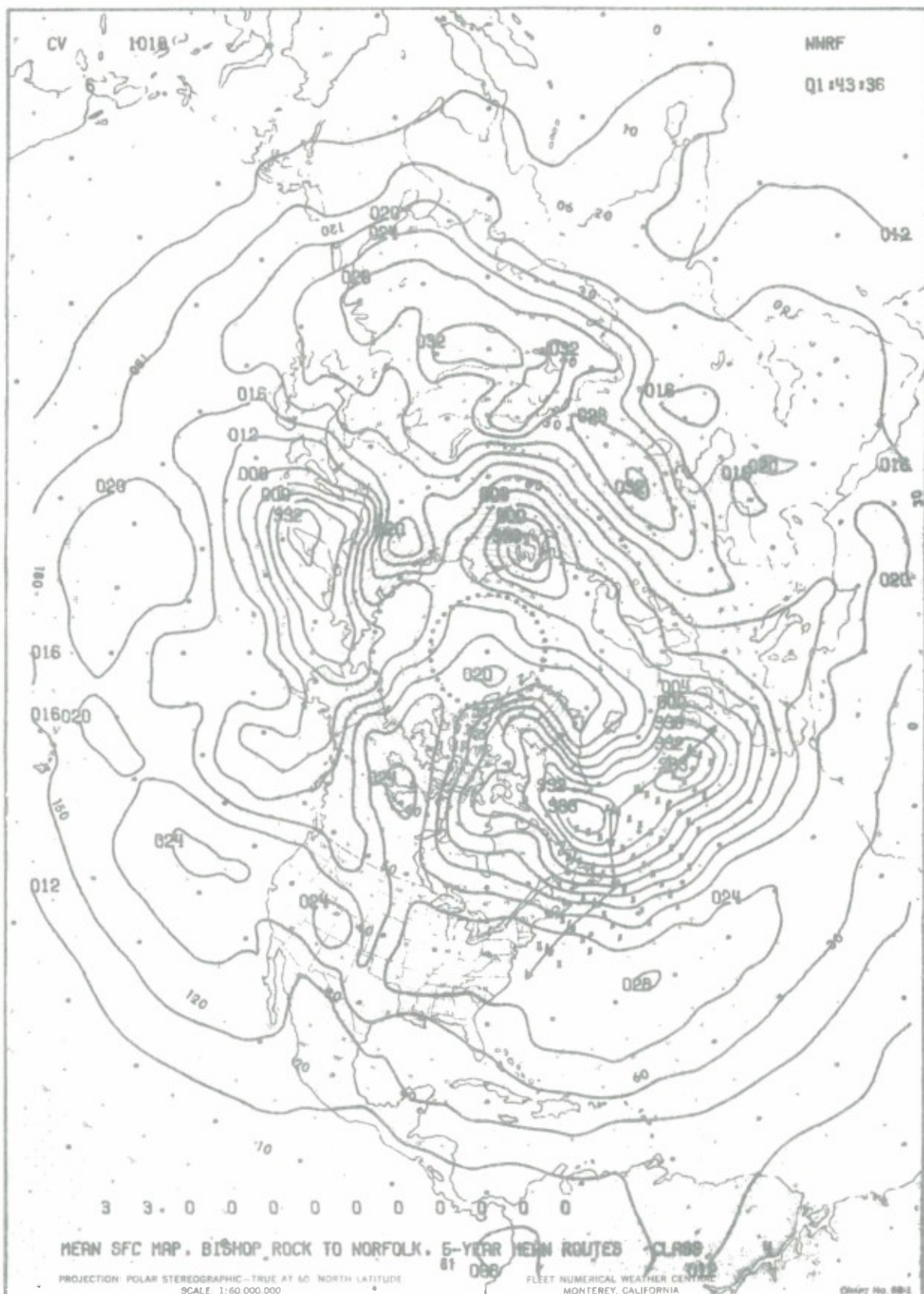
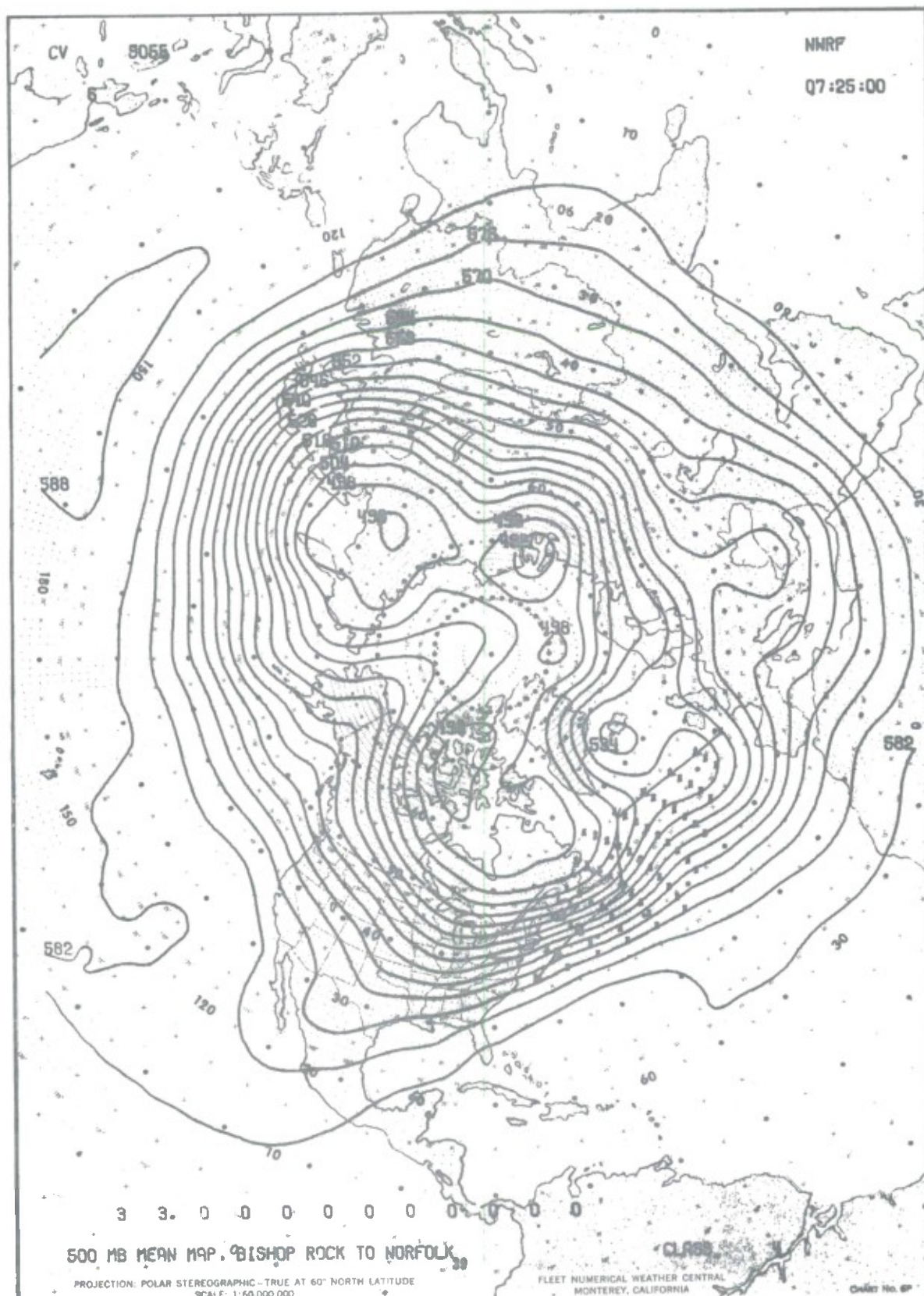


Figure A-1(a).



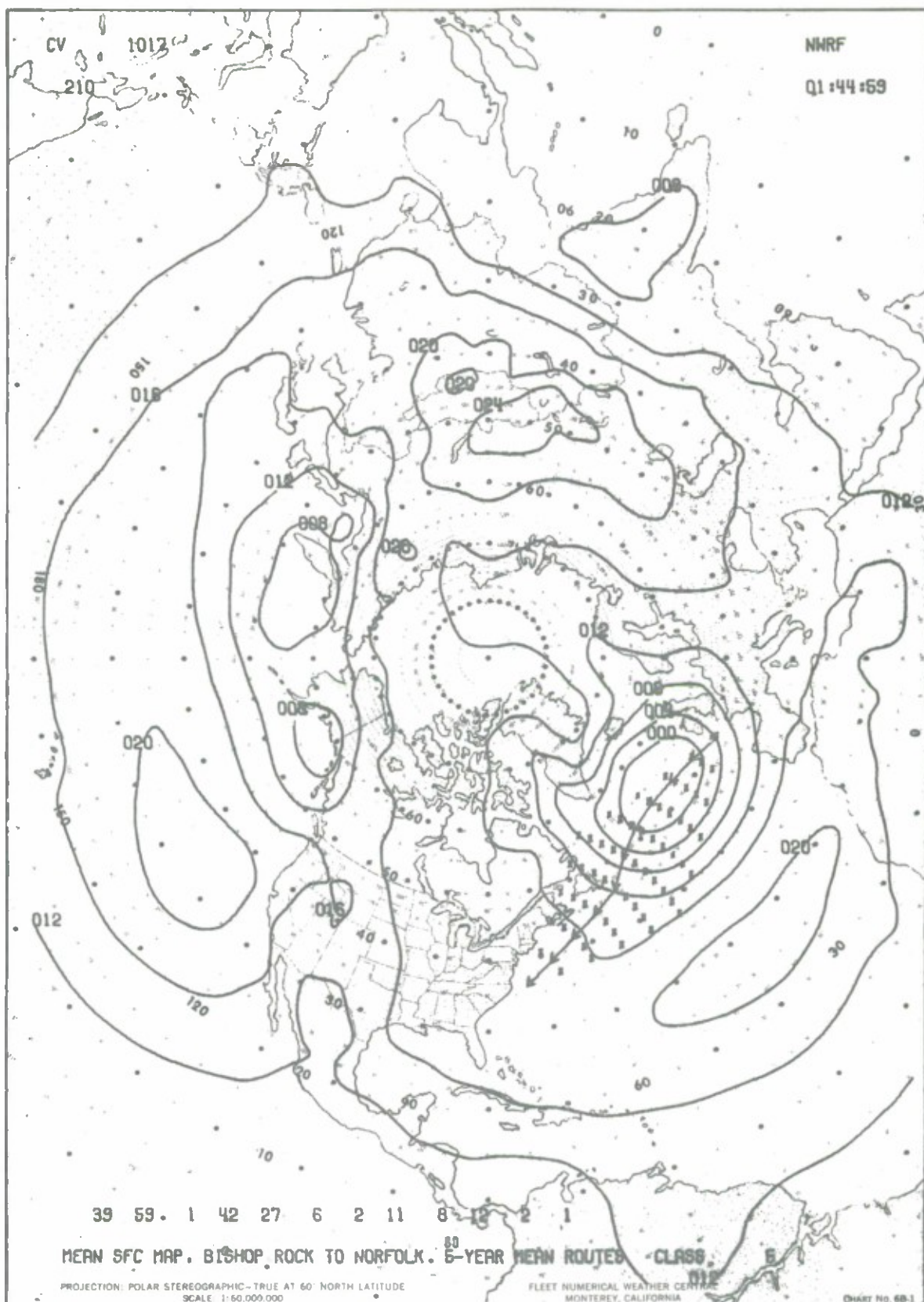
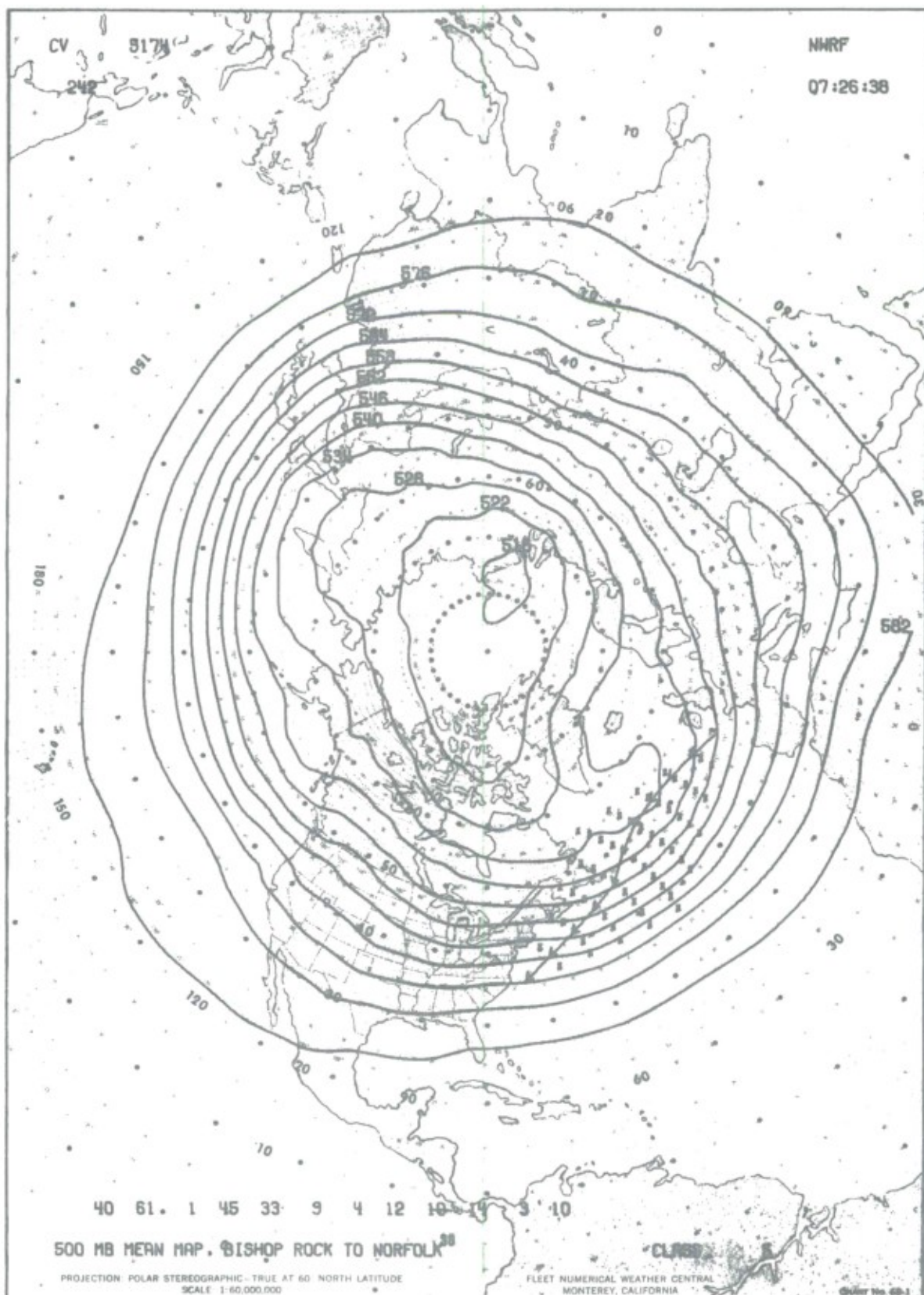


Figure A-2(a).



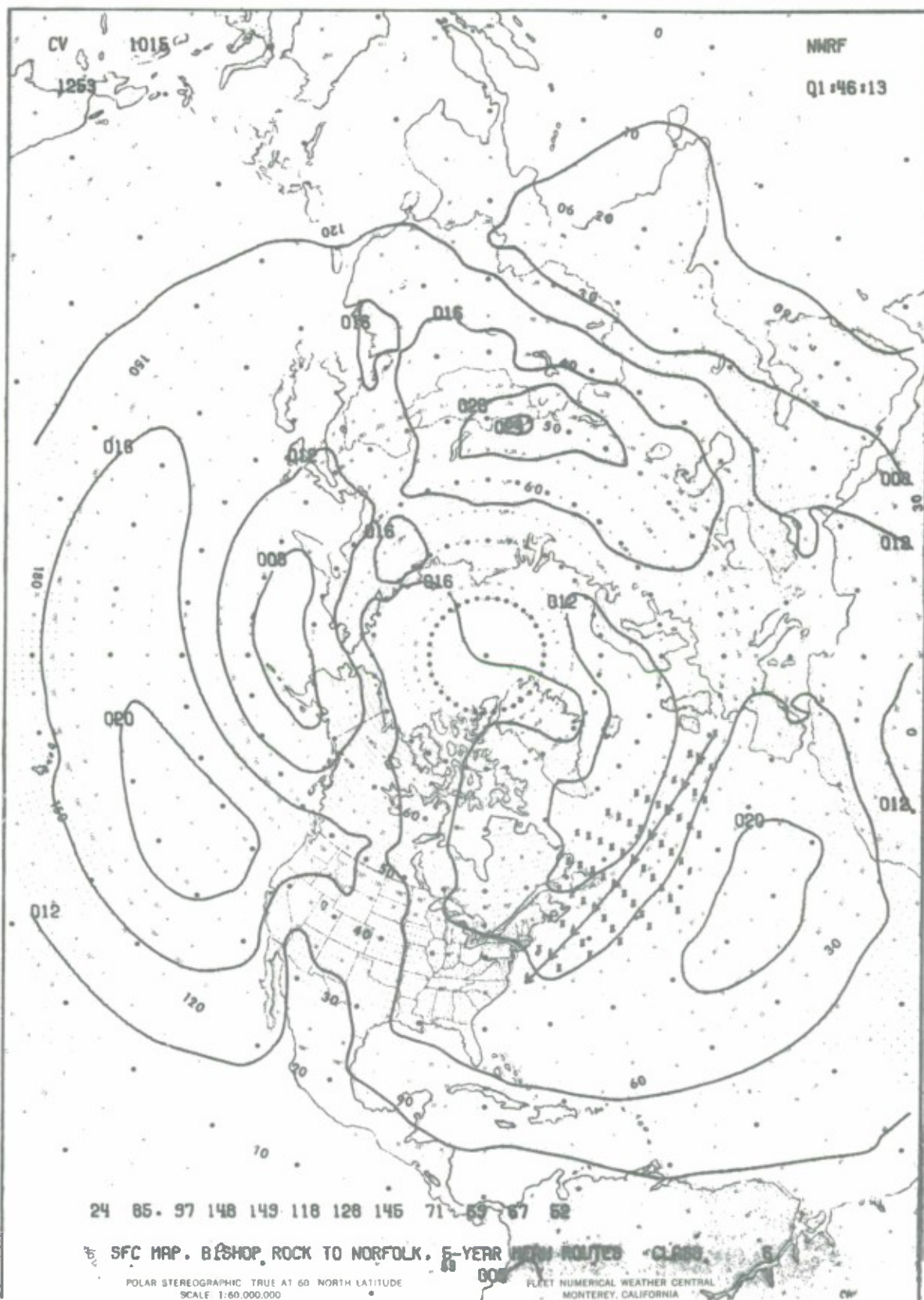


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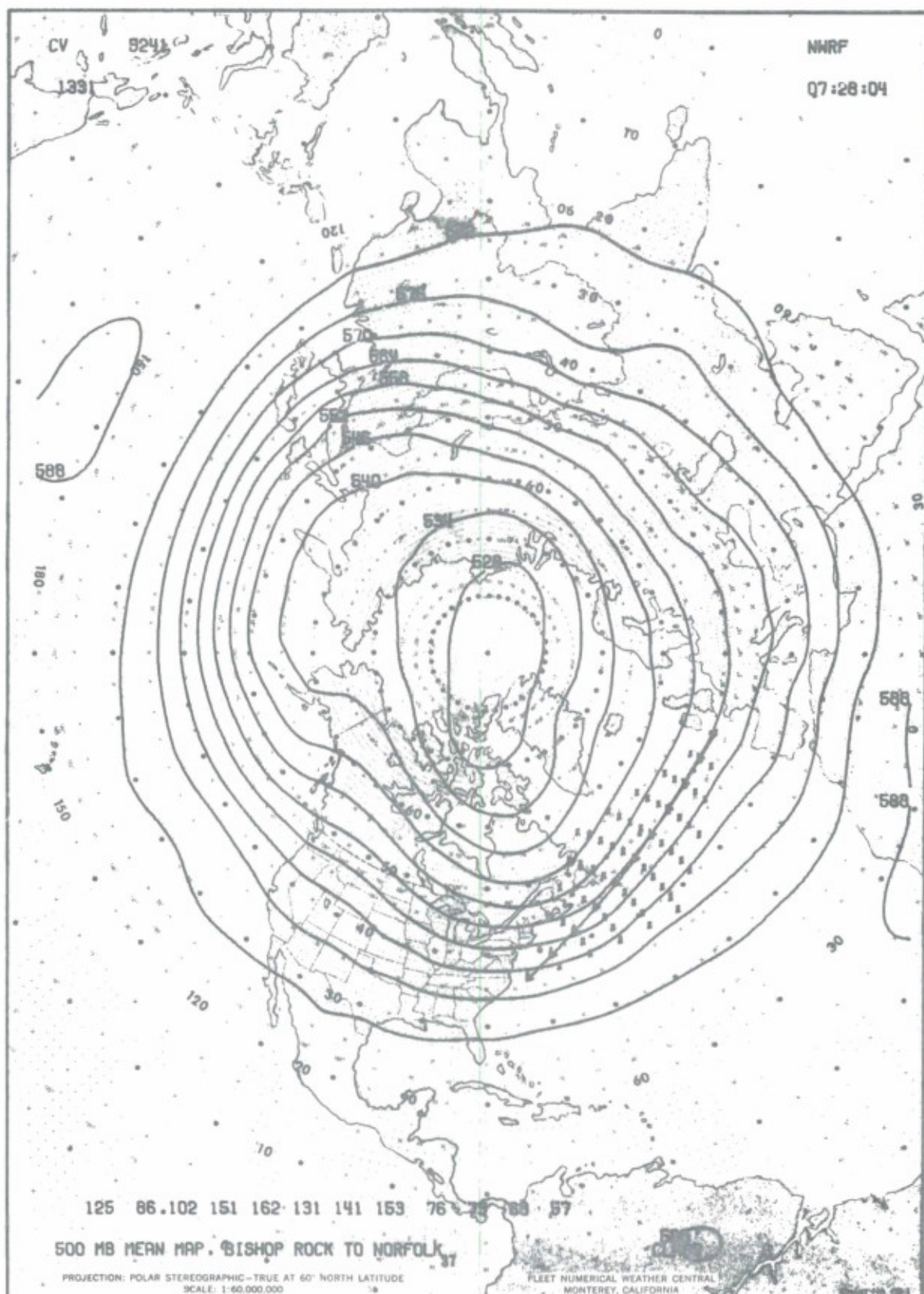


Figure A-3(b).

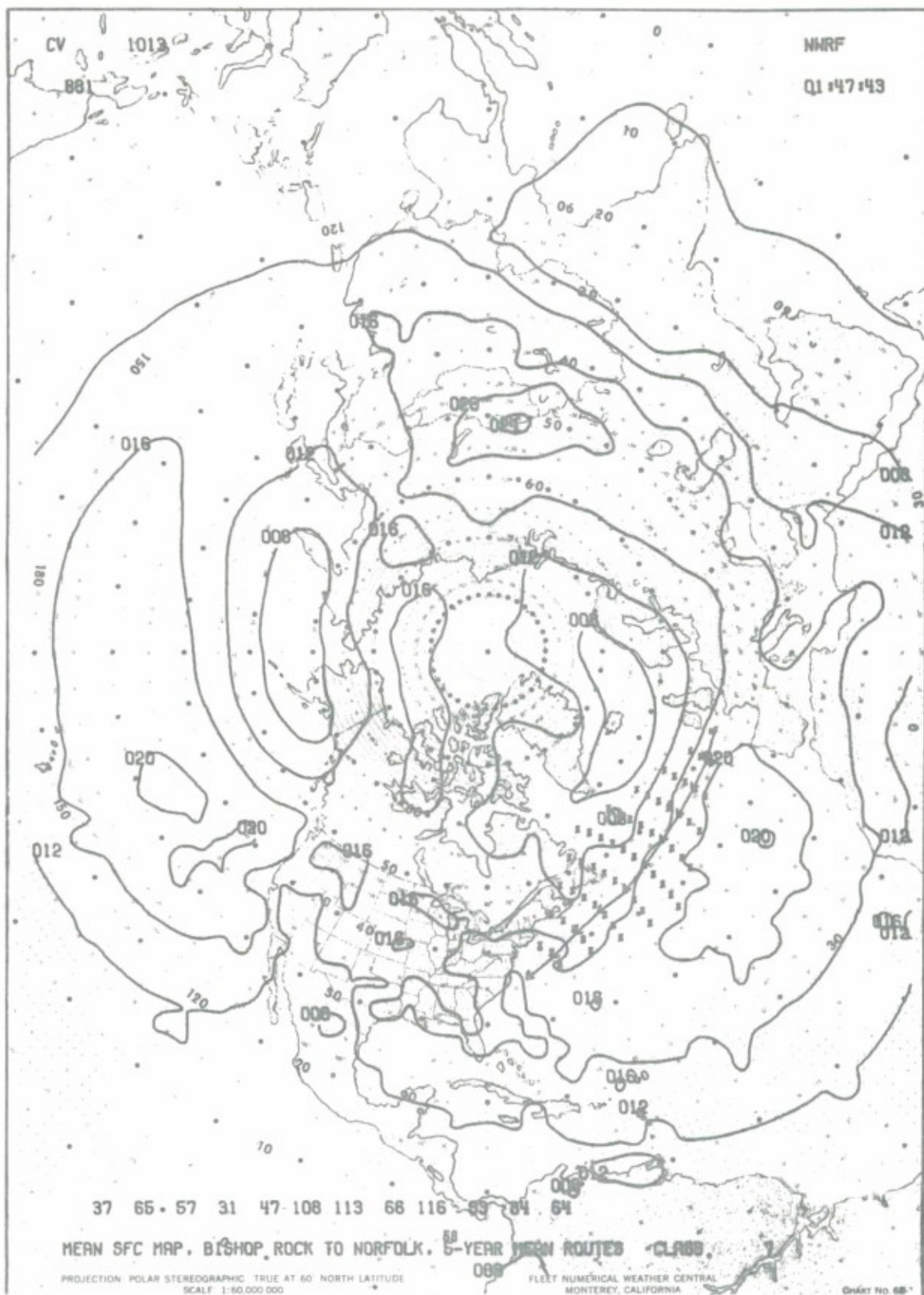


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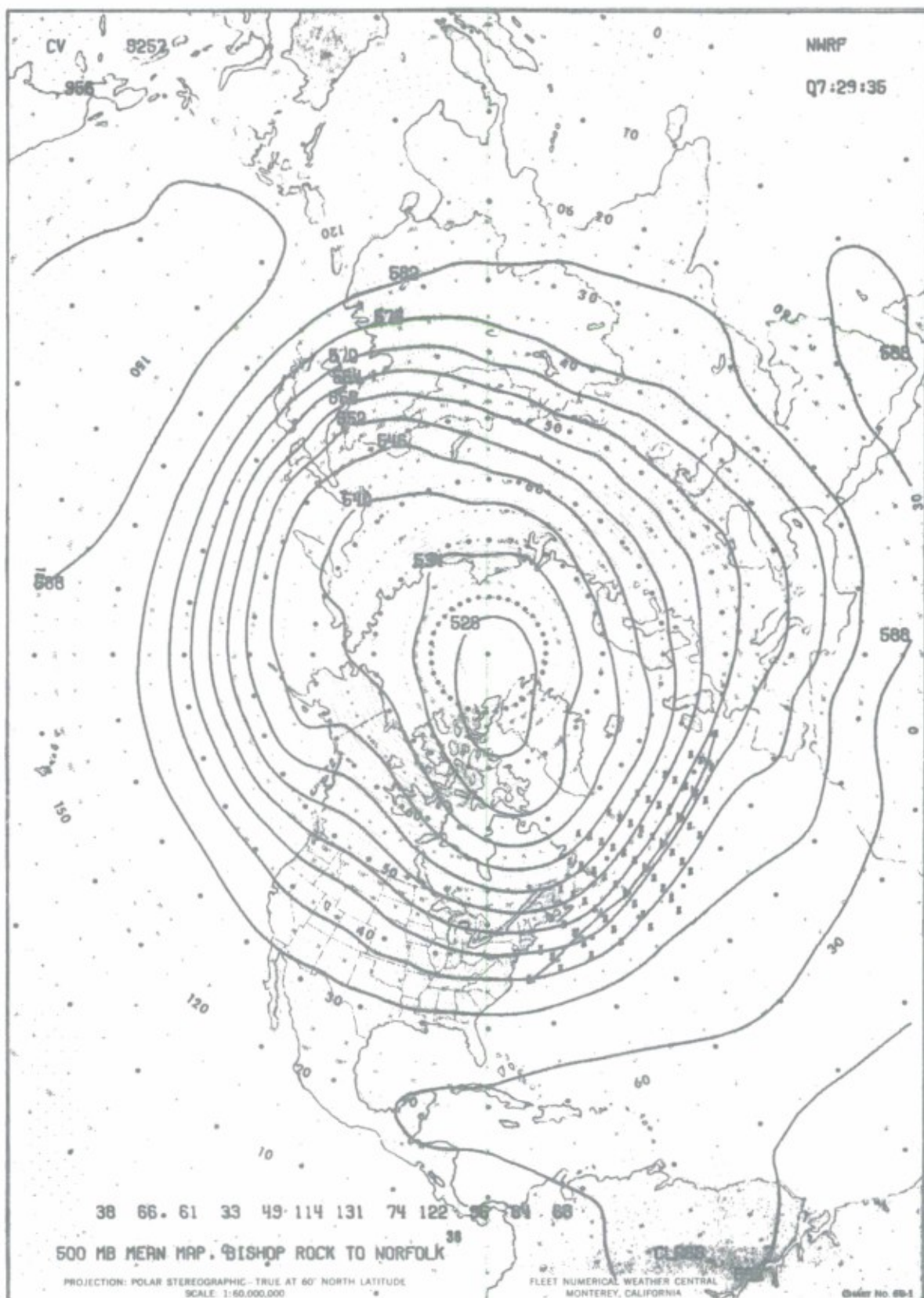
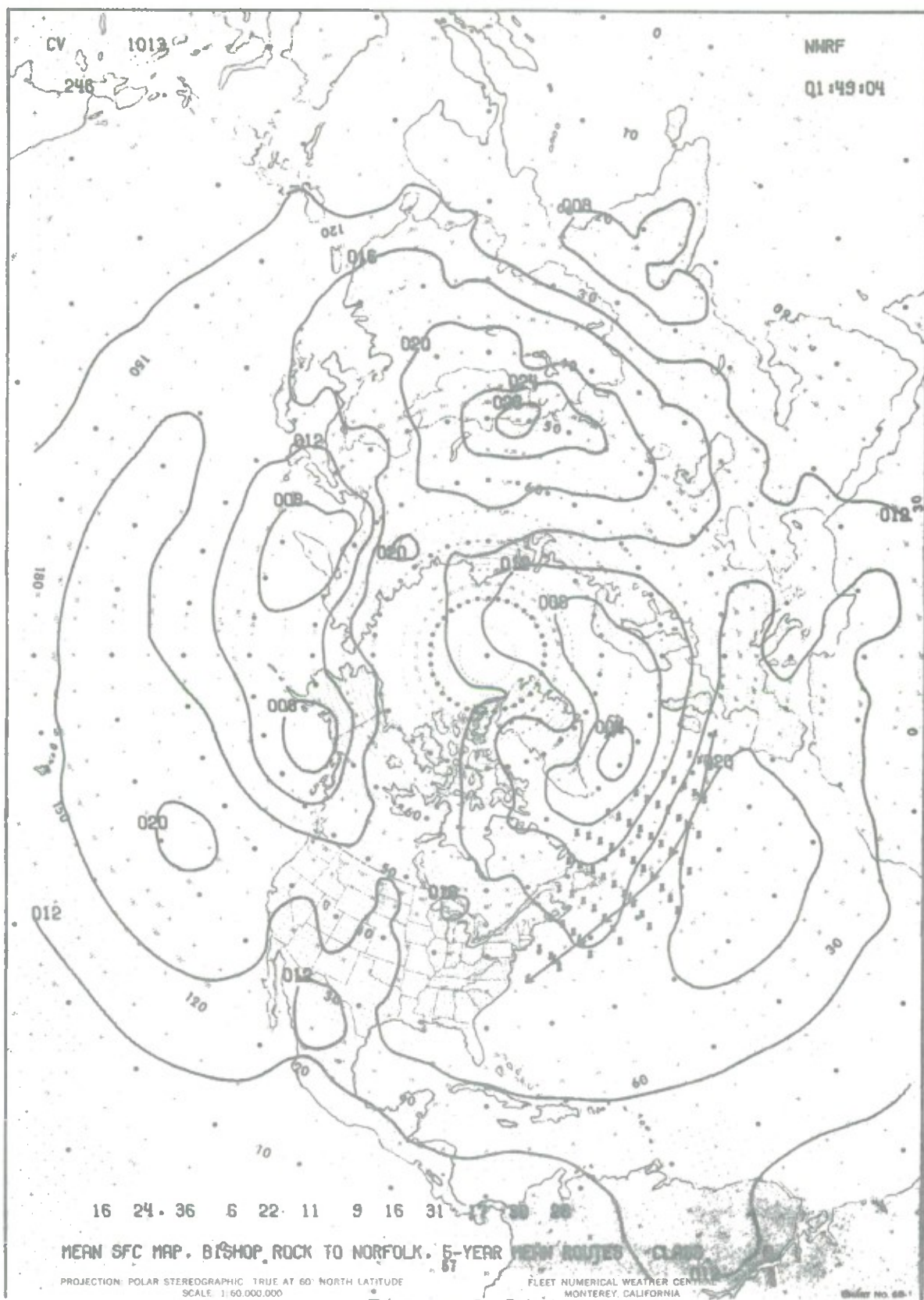


Figure A-4(b).



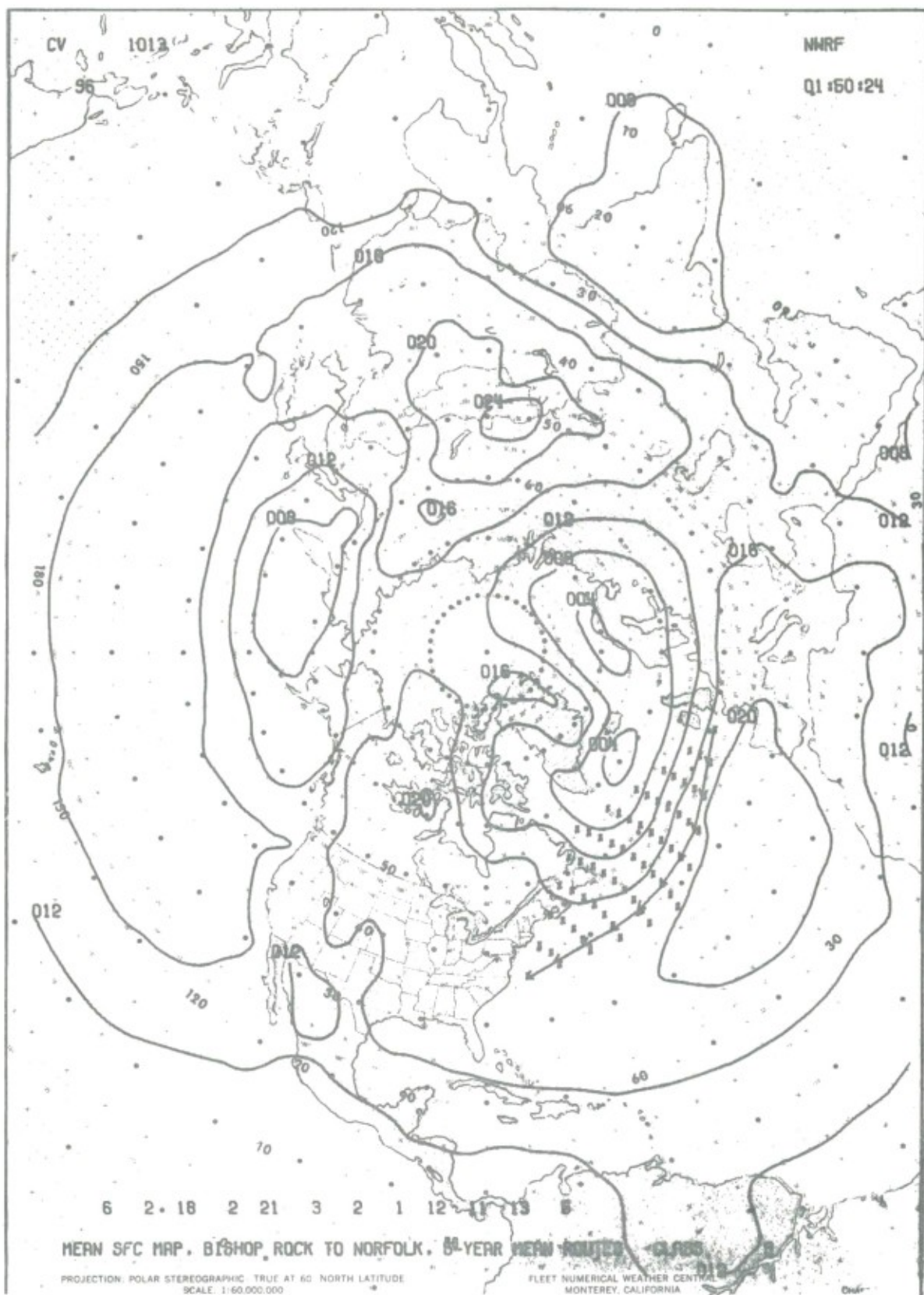


Figure A-6(a).

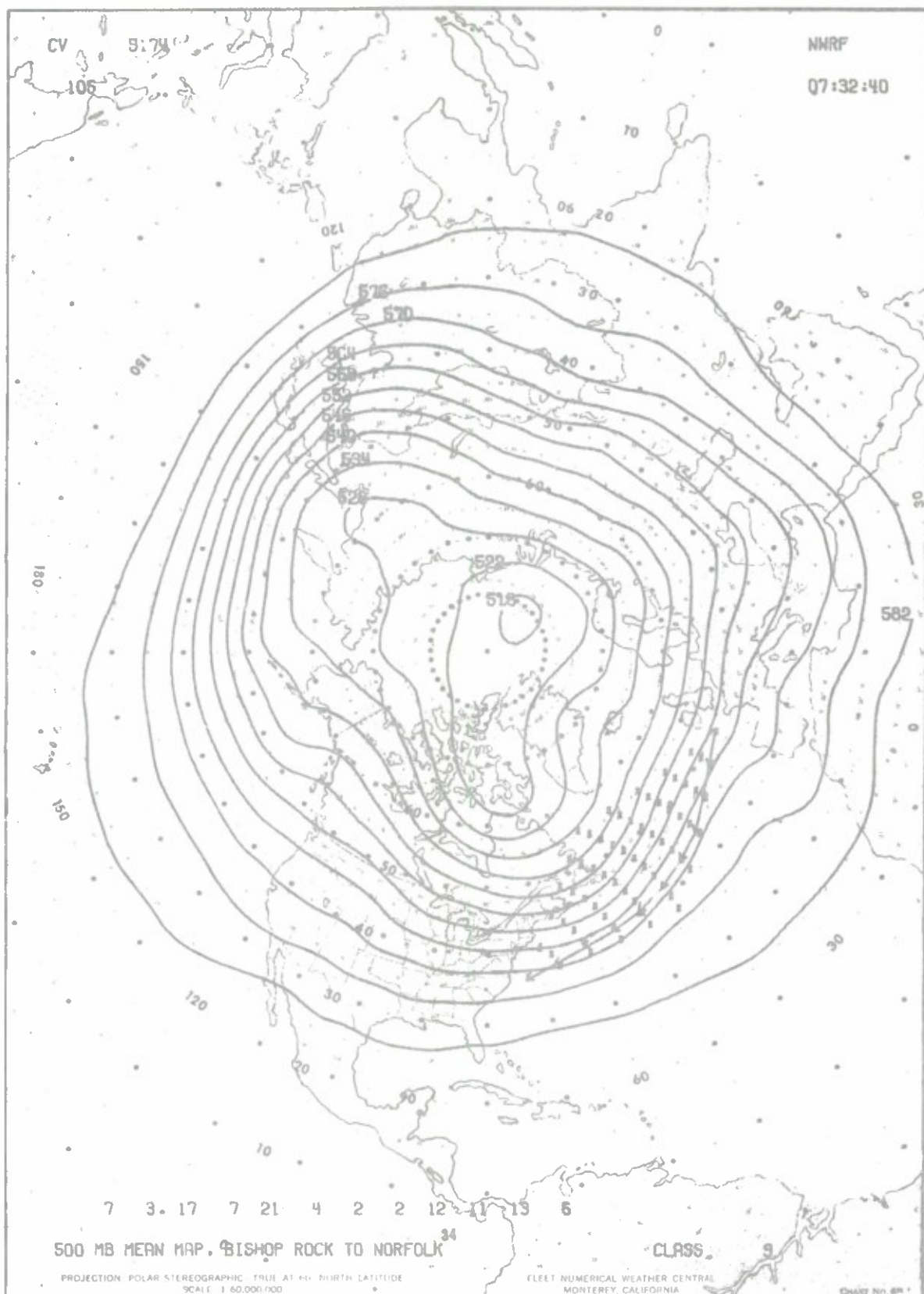
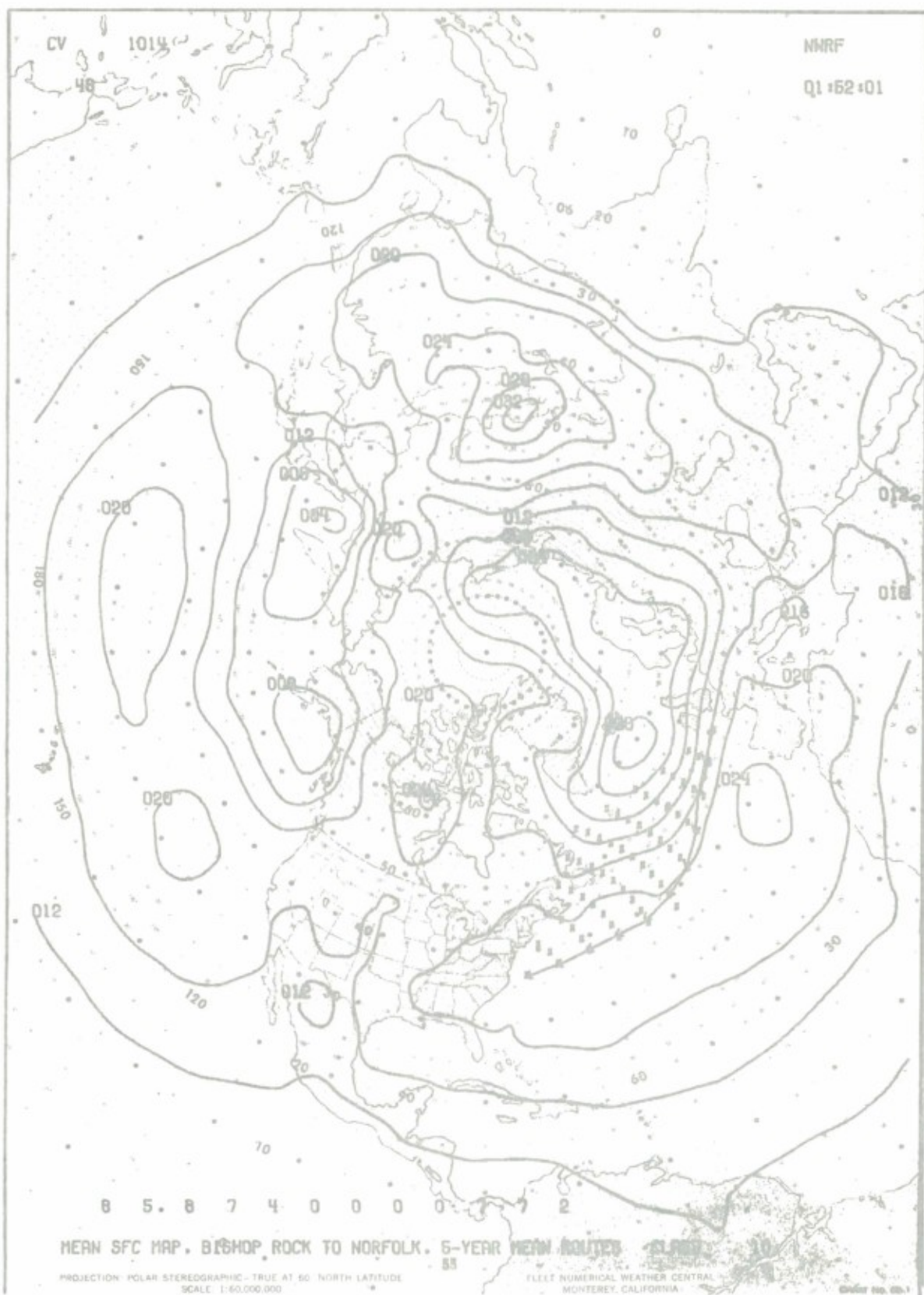
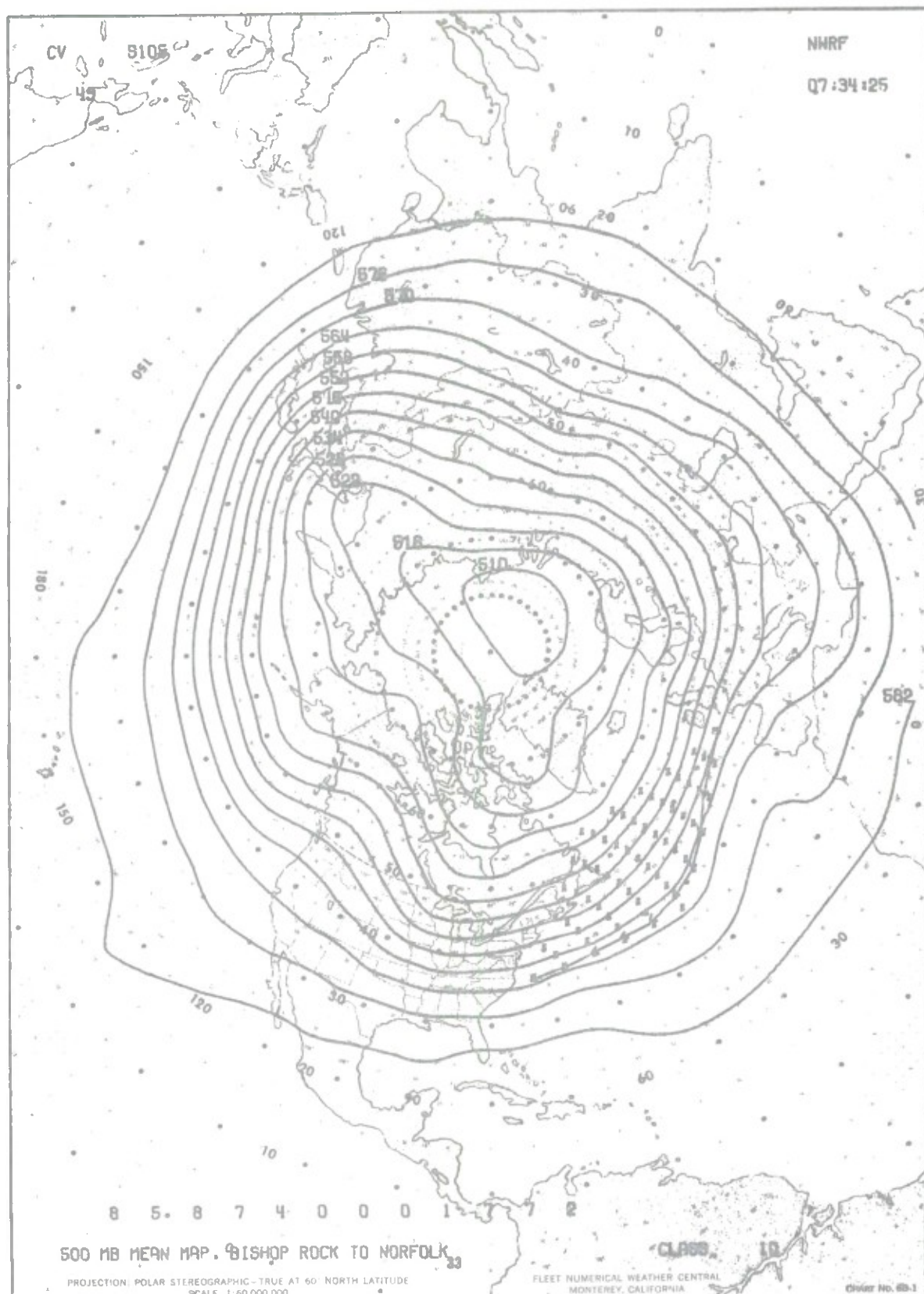


Figure A-6 b).





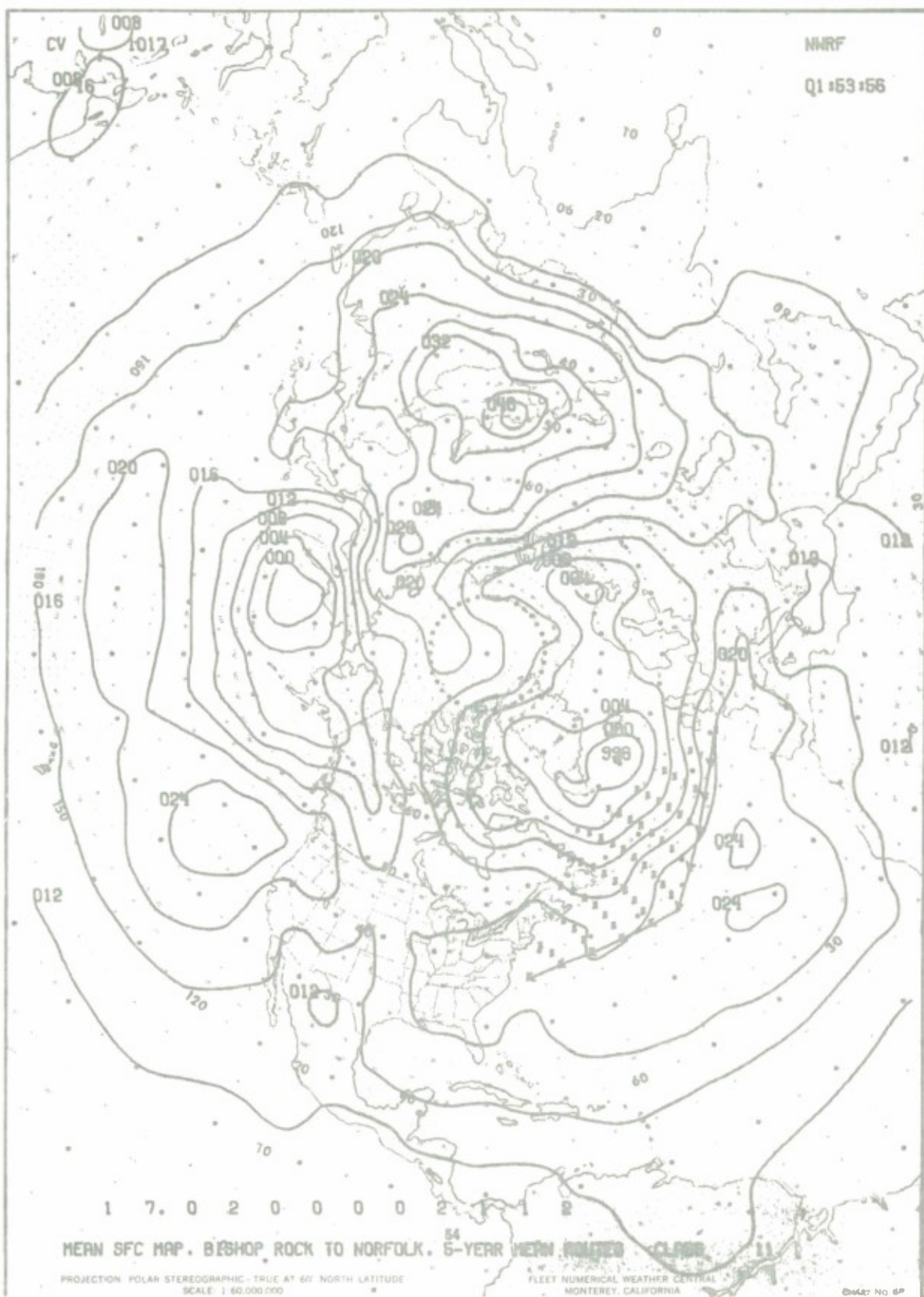


Figure A-8(a).

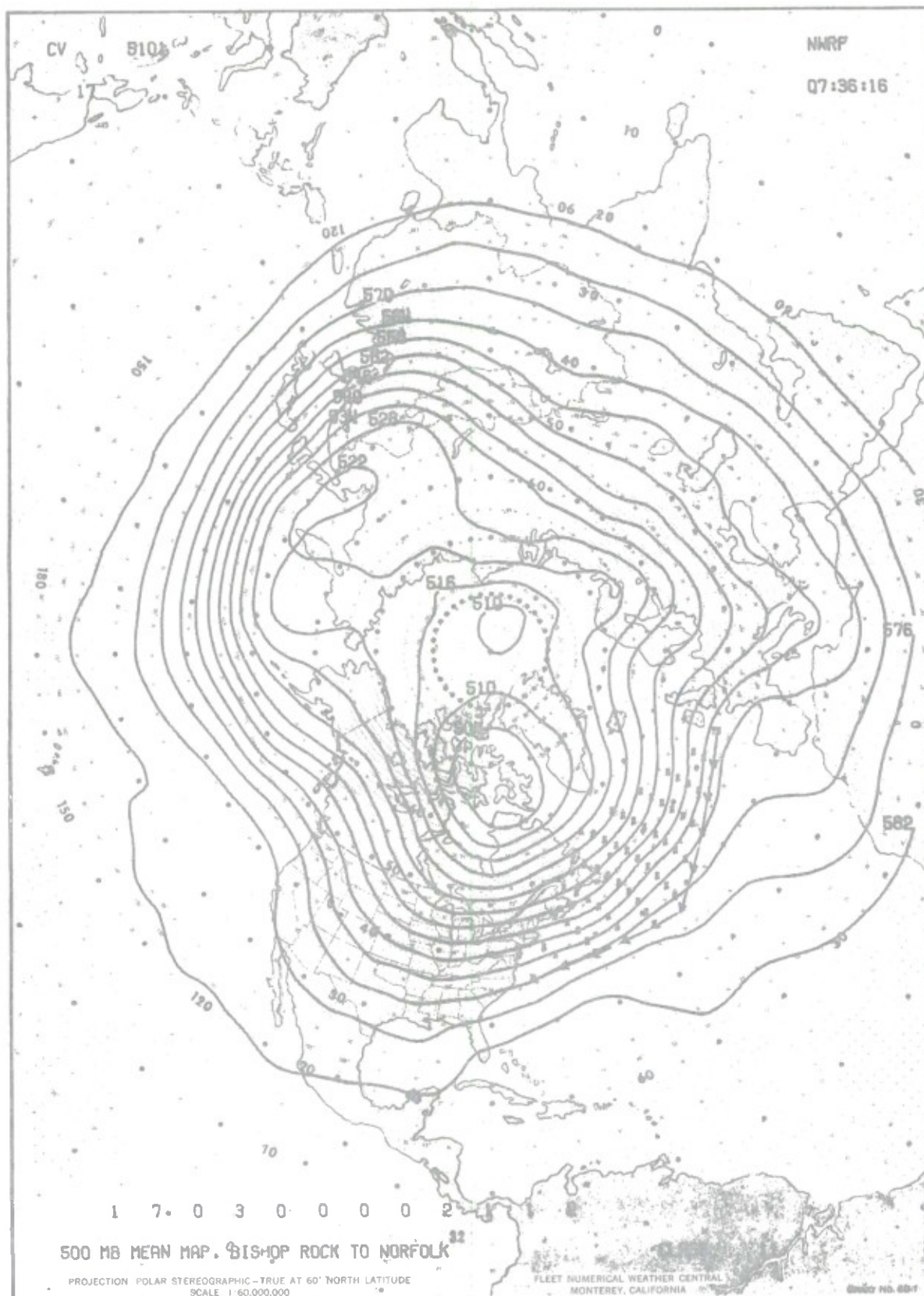


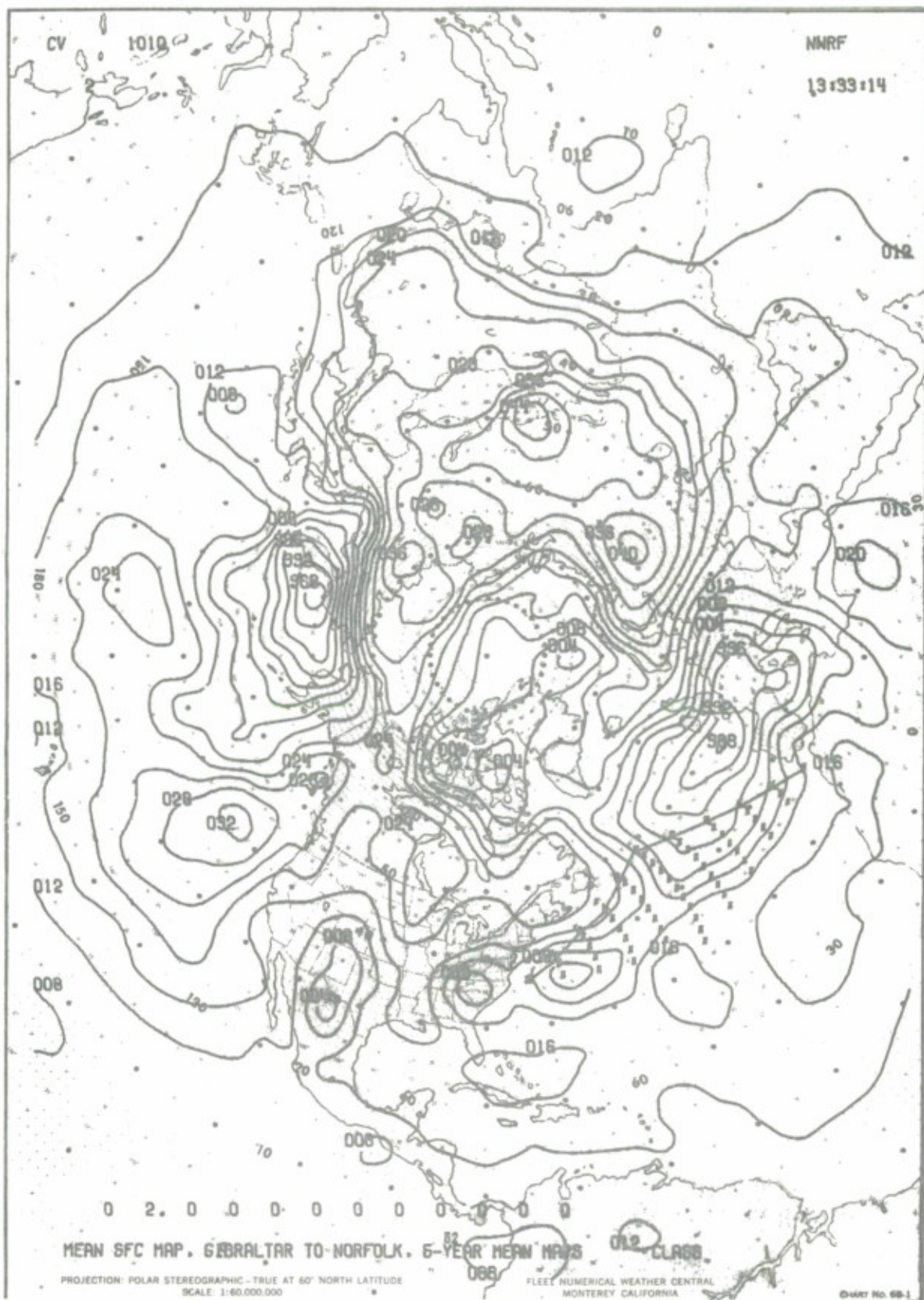
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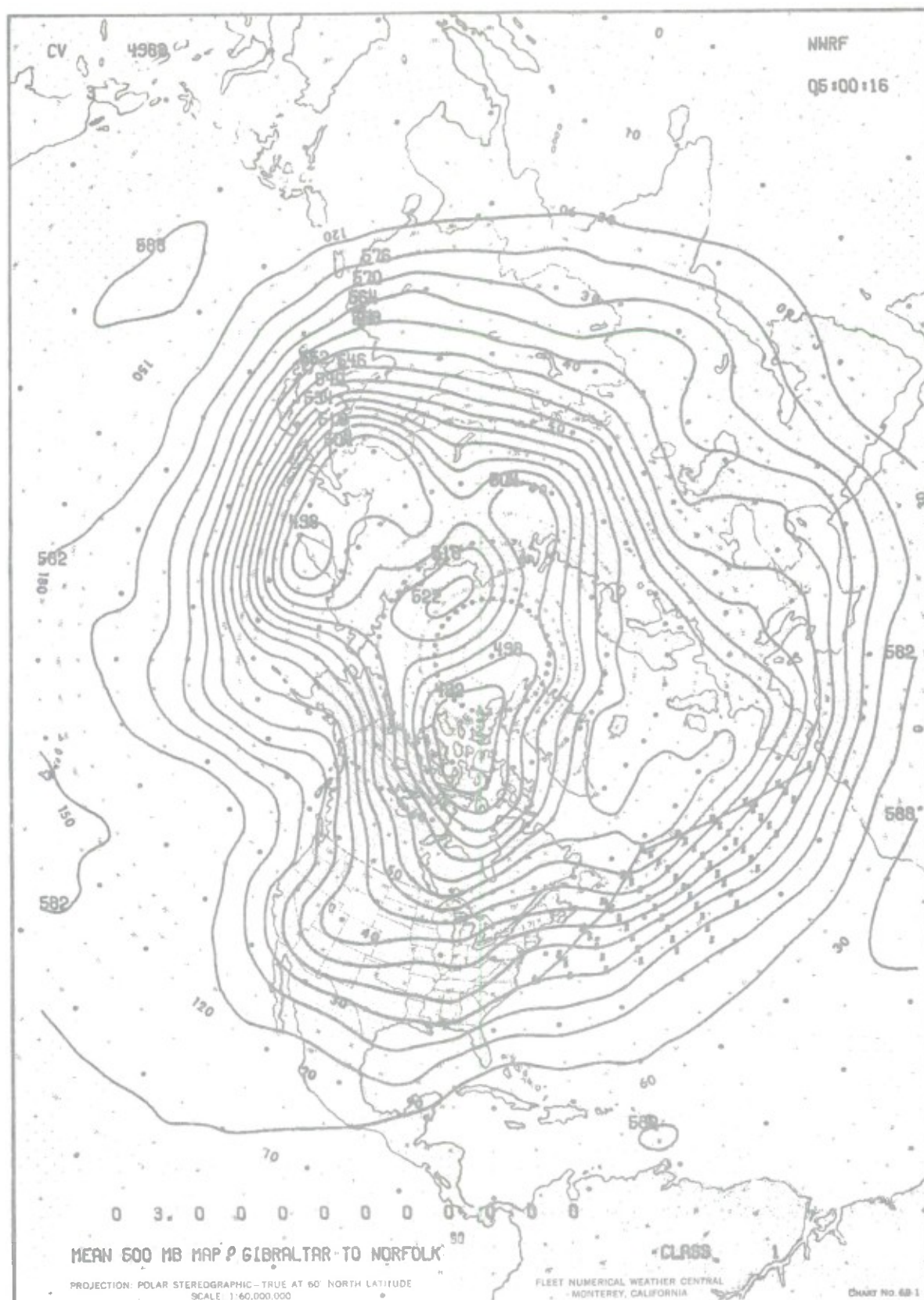
APPENDIX B

GIBRALTAR TO NORFOLK

15-KNOT VESSEL

FIGURE B-1	Class 1
FIGURE B-2	Class 2
FIGURE B-3	Class 3
FIGURE B-4	Class 4
FIGURE B-5	Class 5
FIGURE B-6	Class 6
FIGURE B-7	Class 7
FIGURE B-8	Class 8
FIGURE B-9	Class 9
FIGURE B-10	Class 10
FIGURE B-11	Class 11





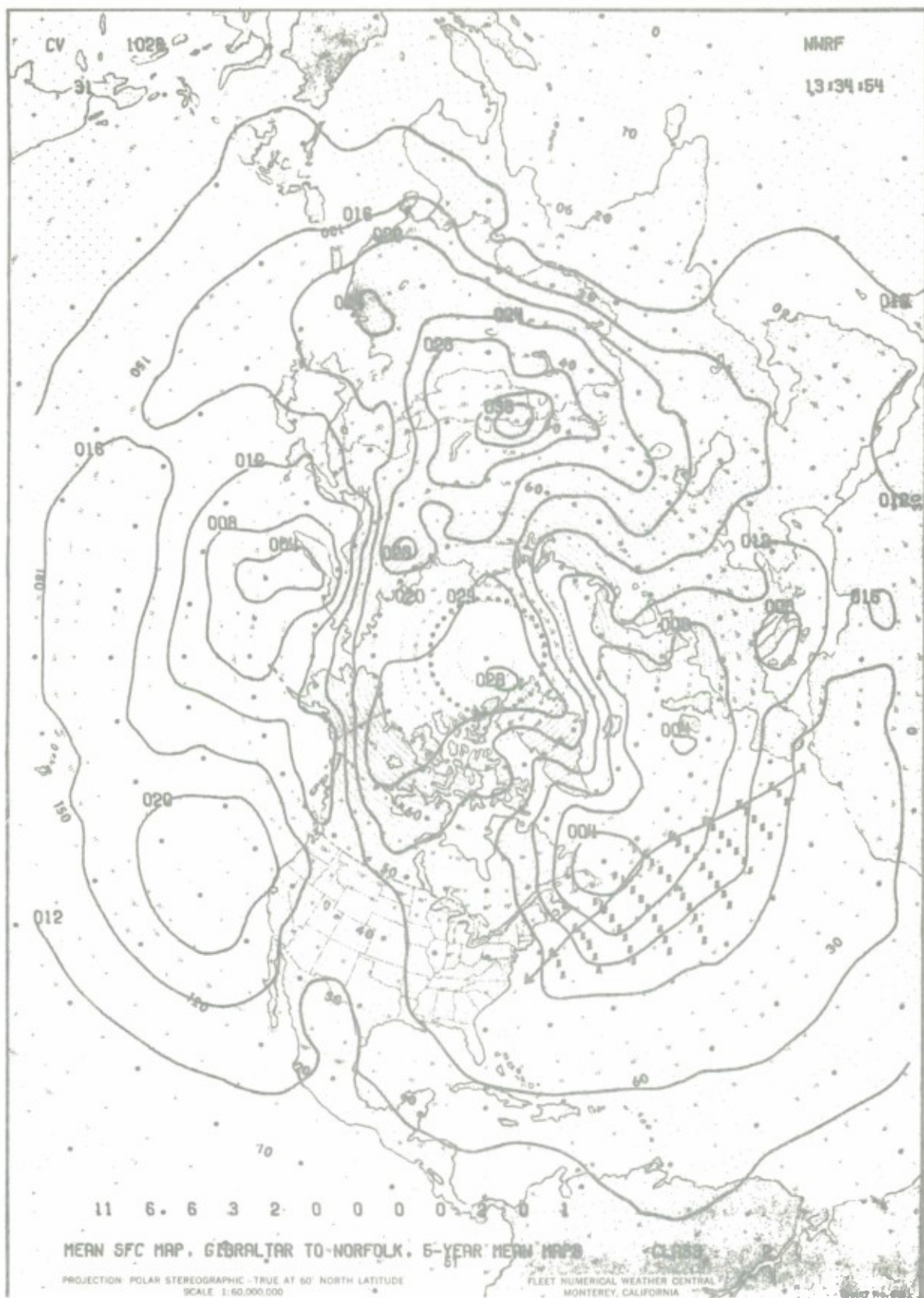
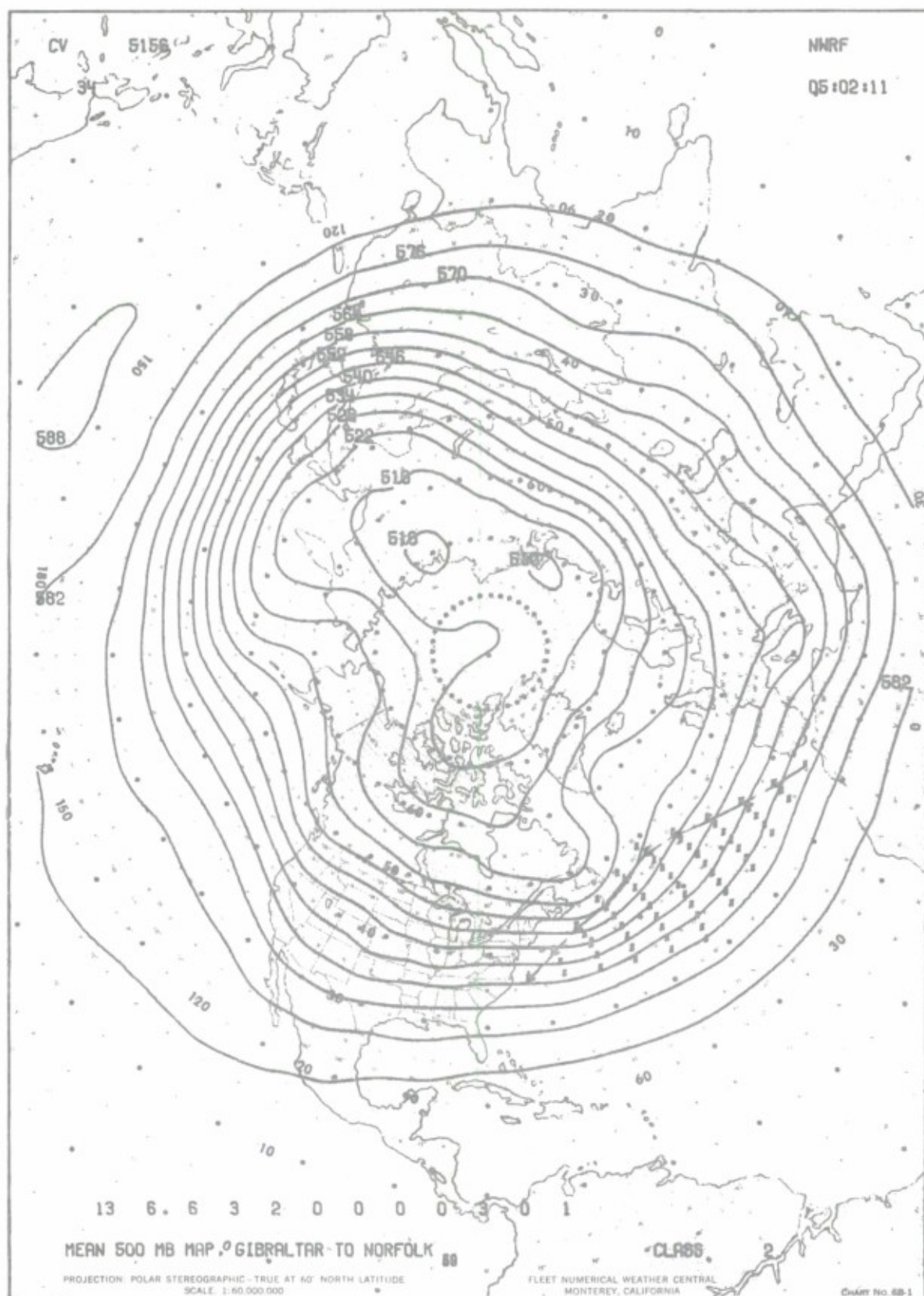
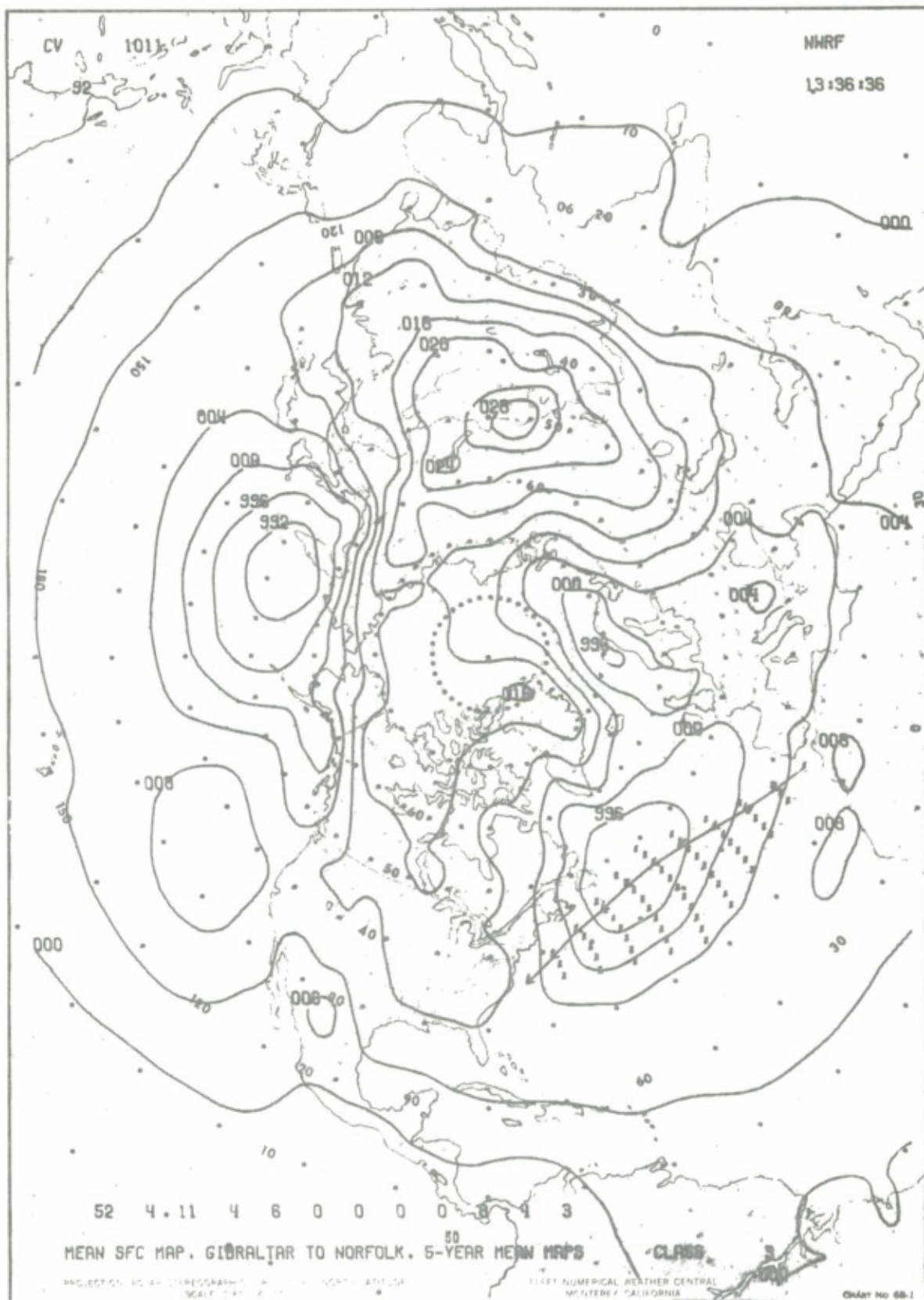


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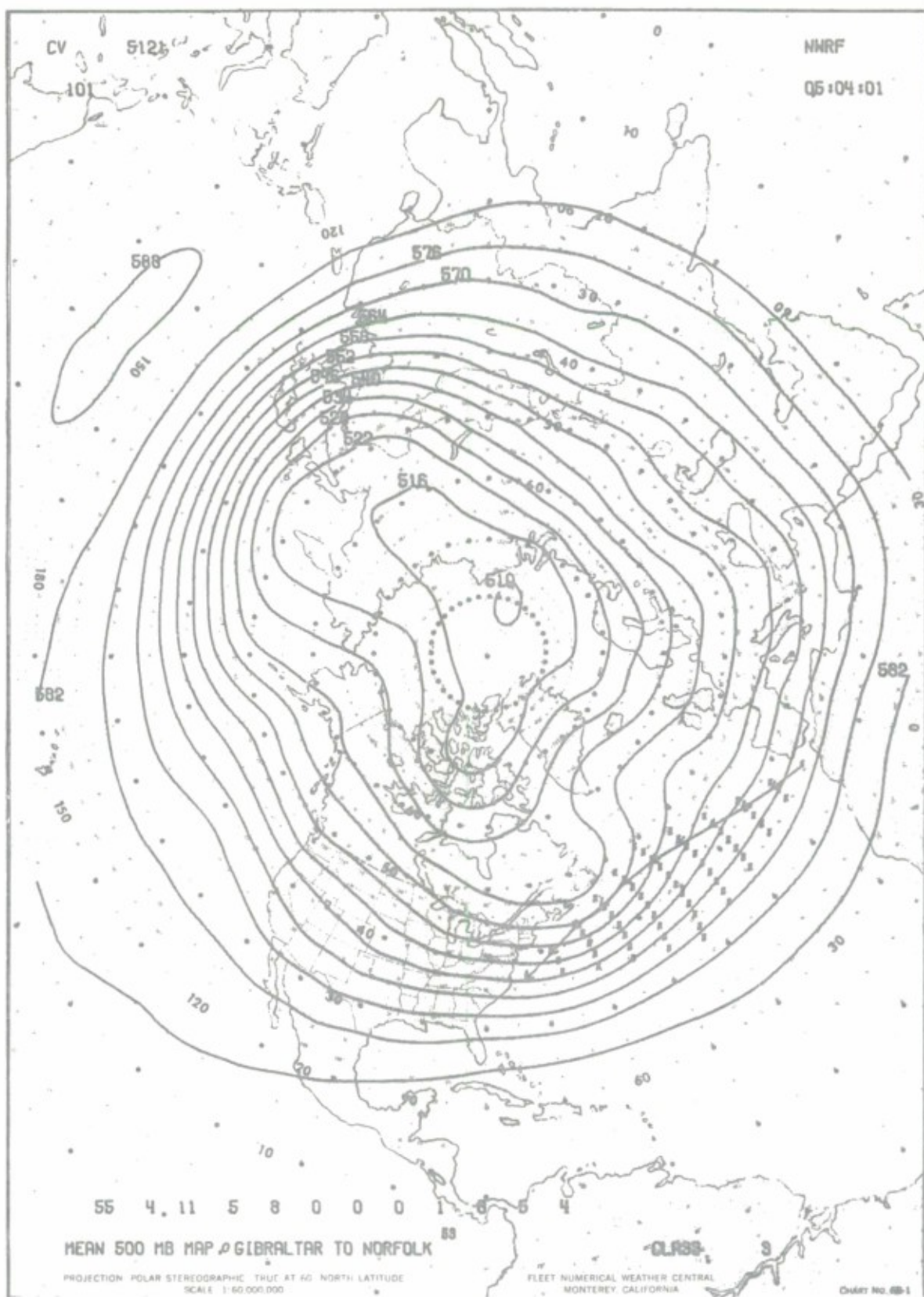


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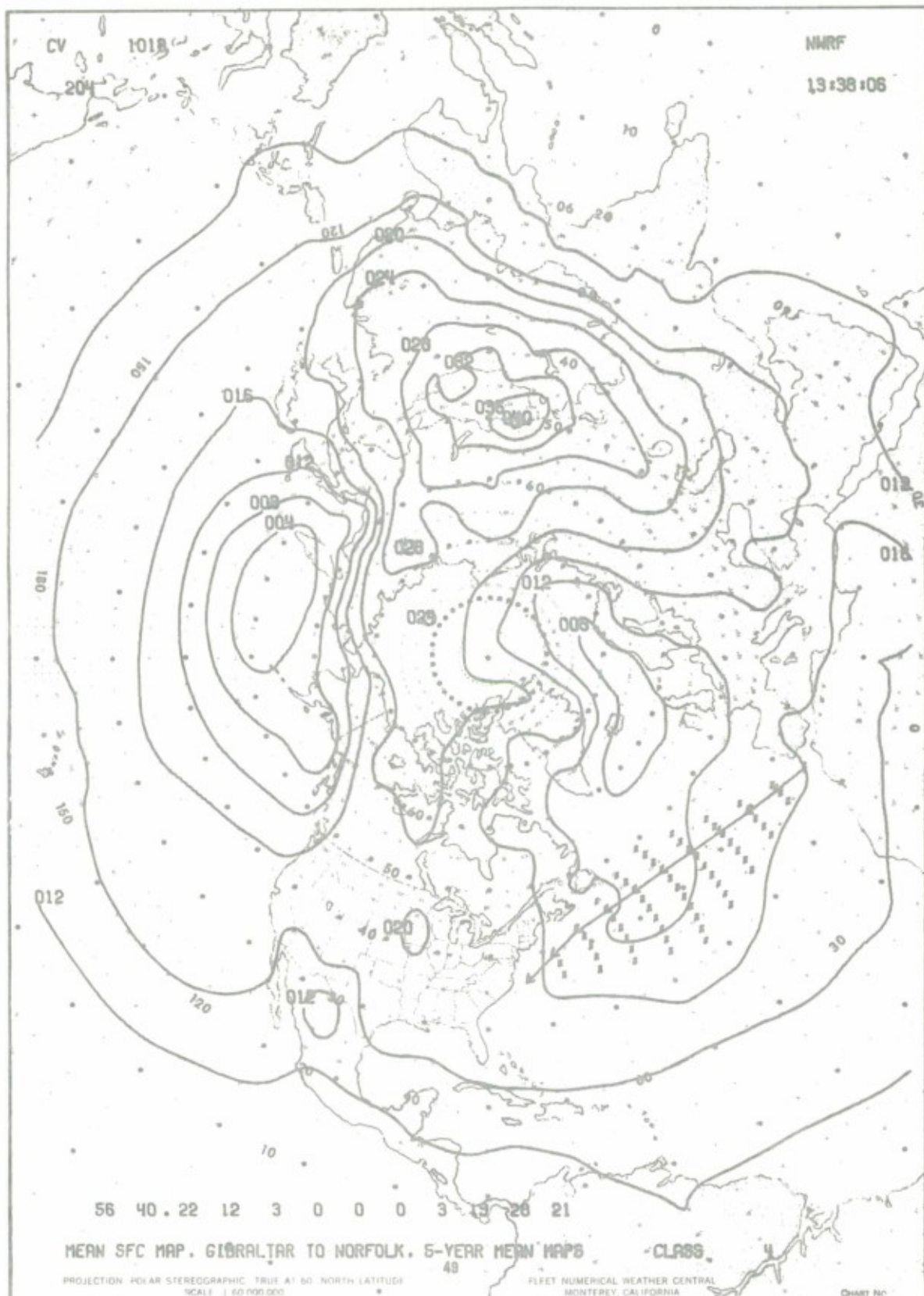


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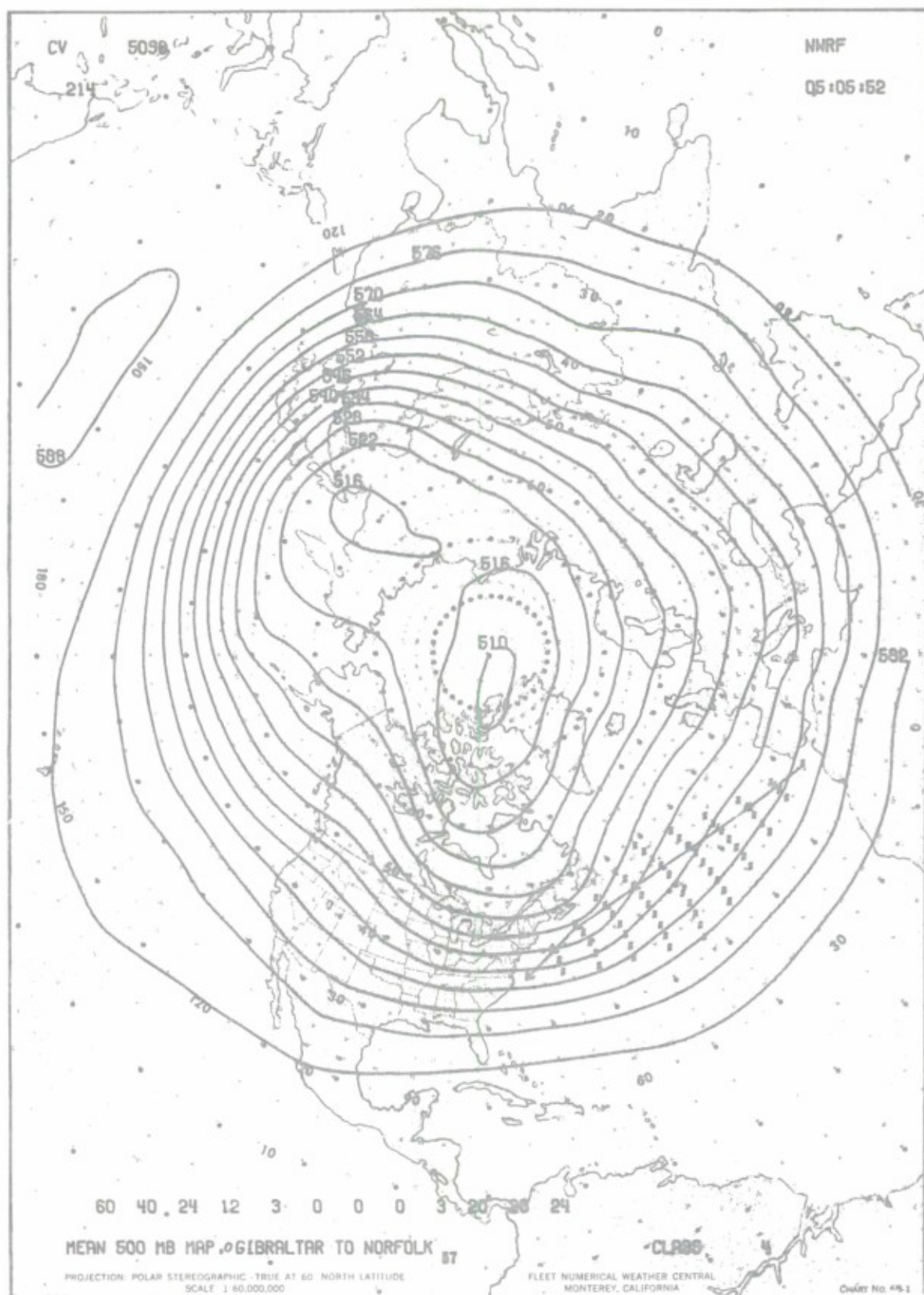


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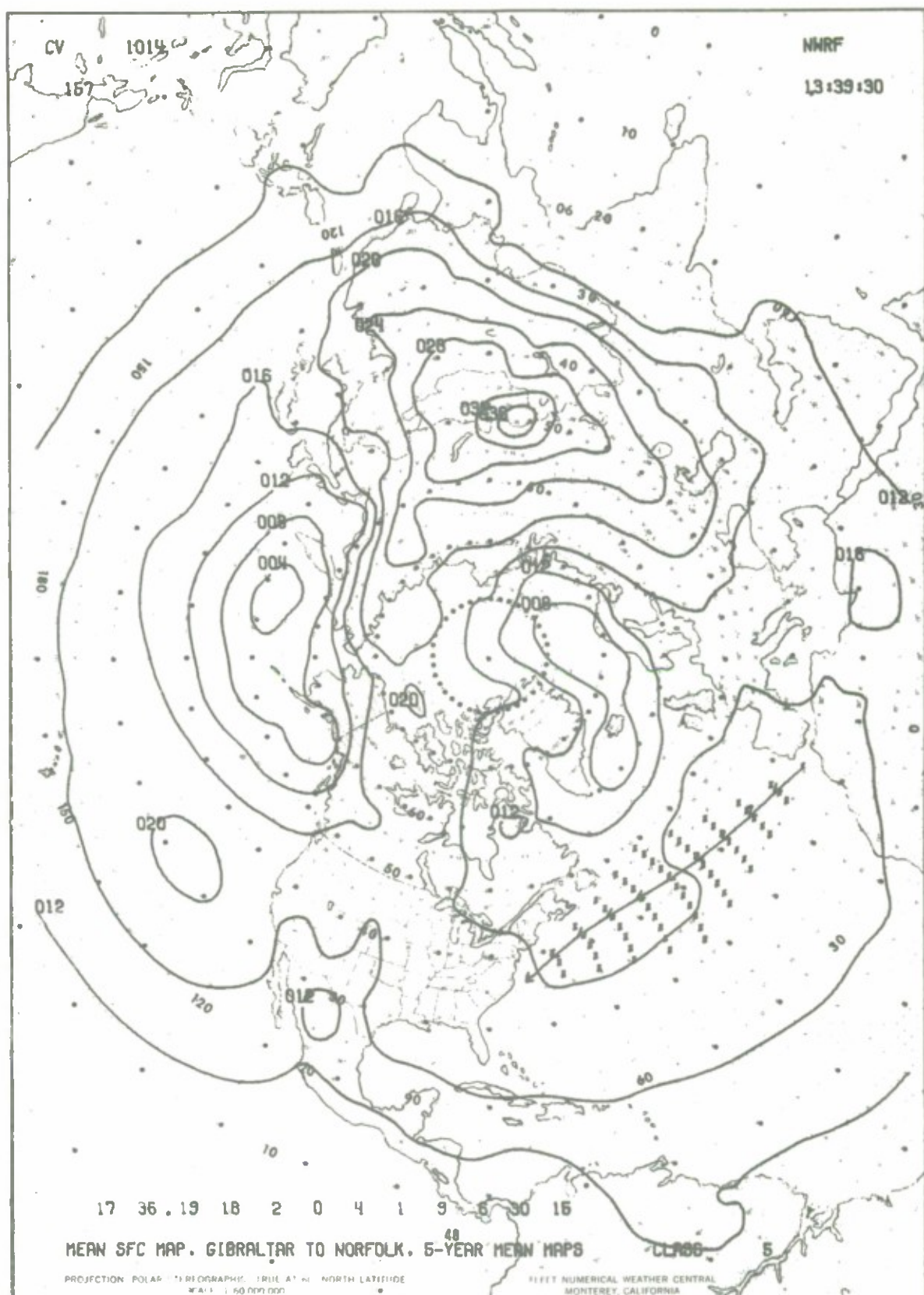


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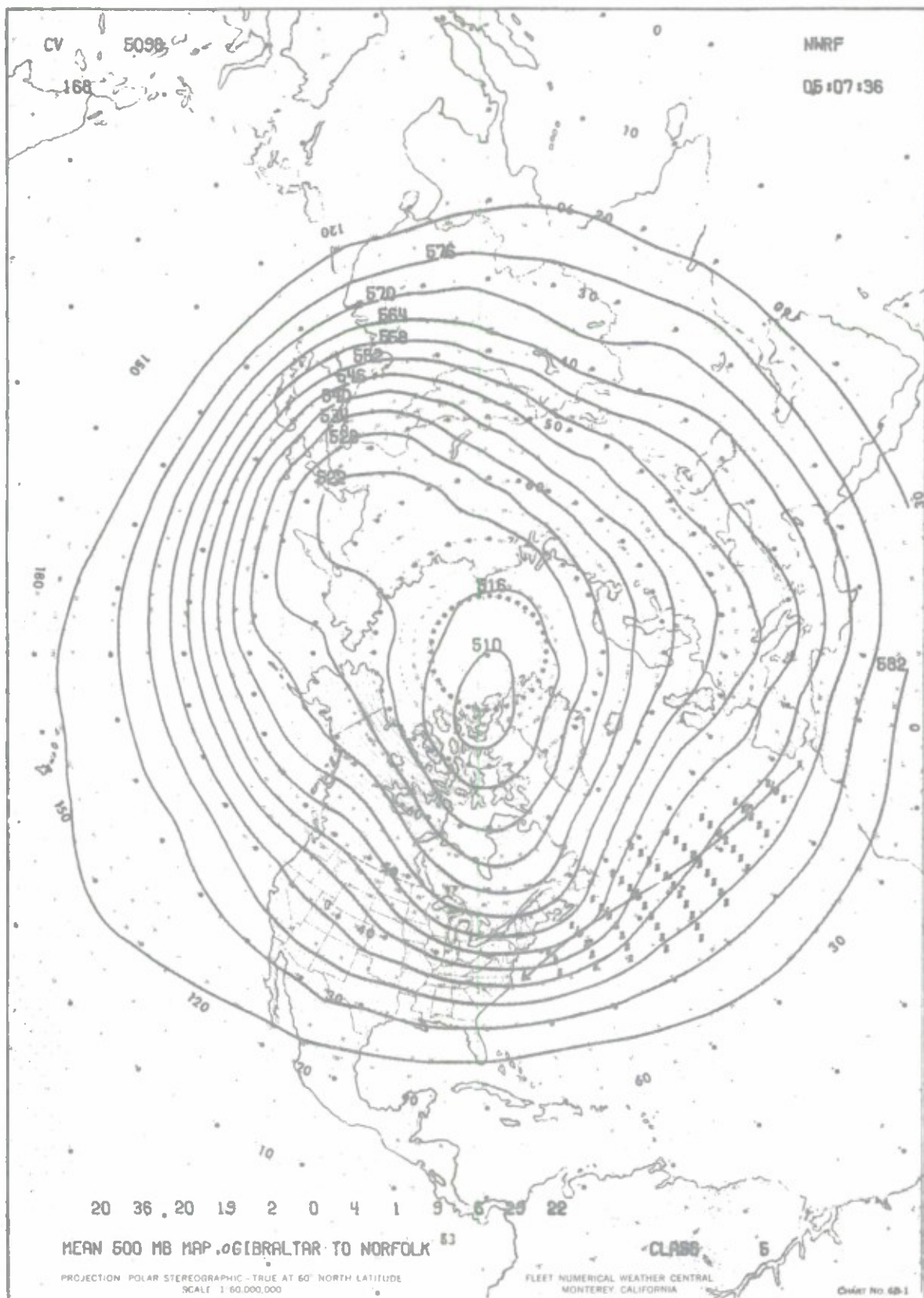


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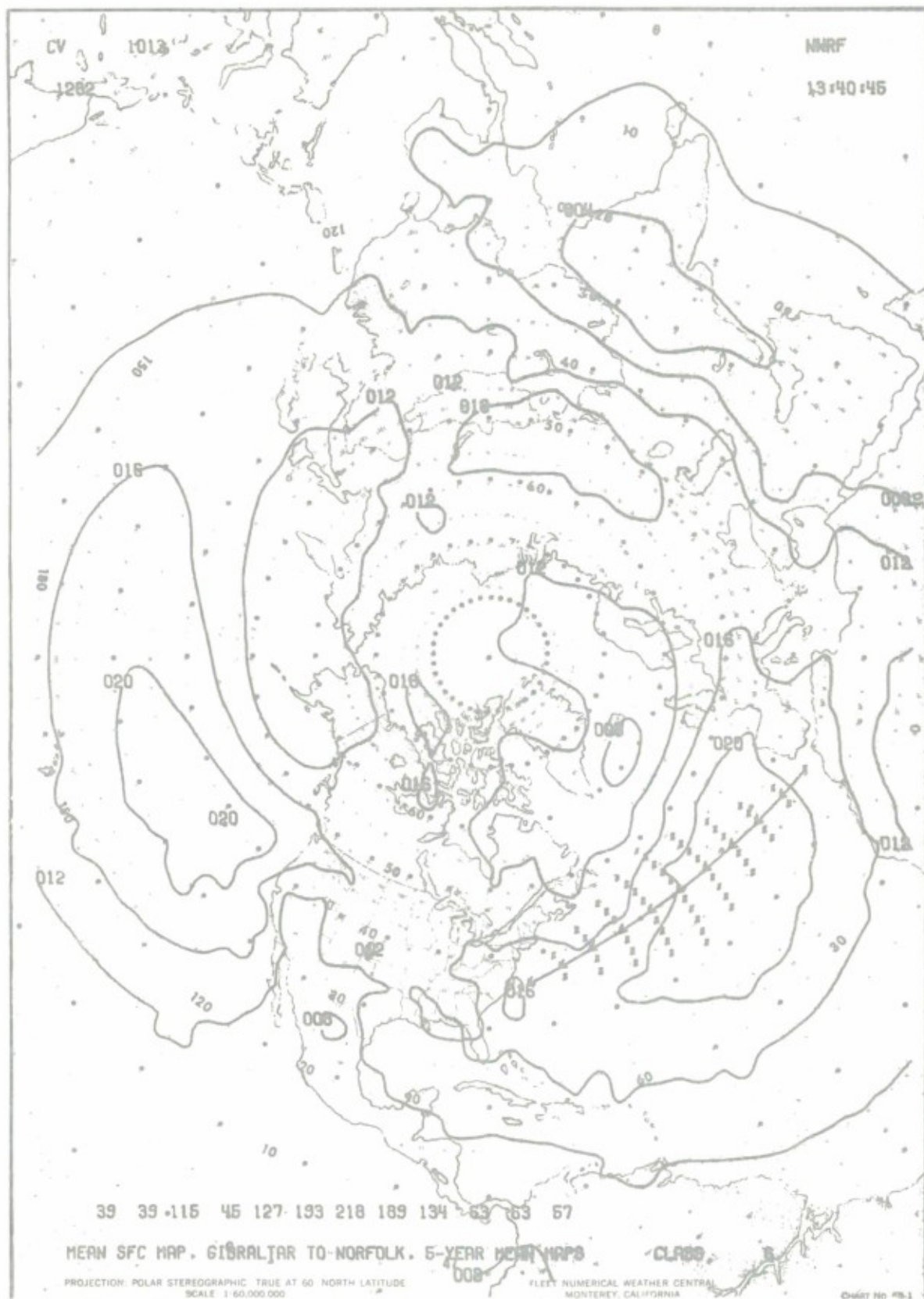


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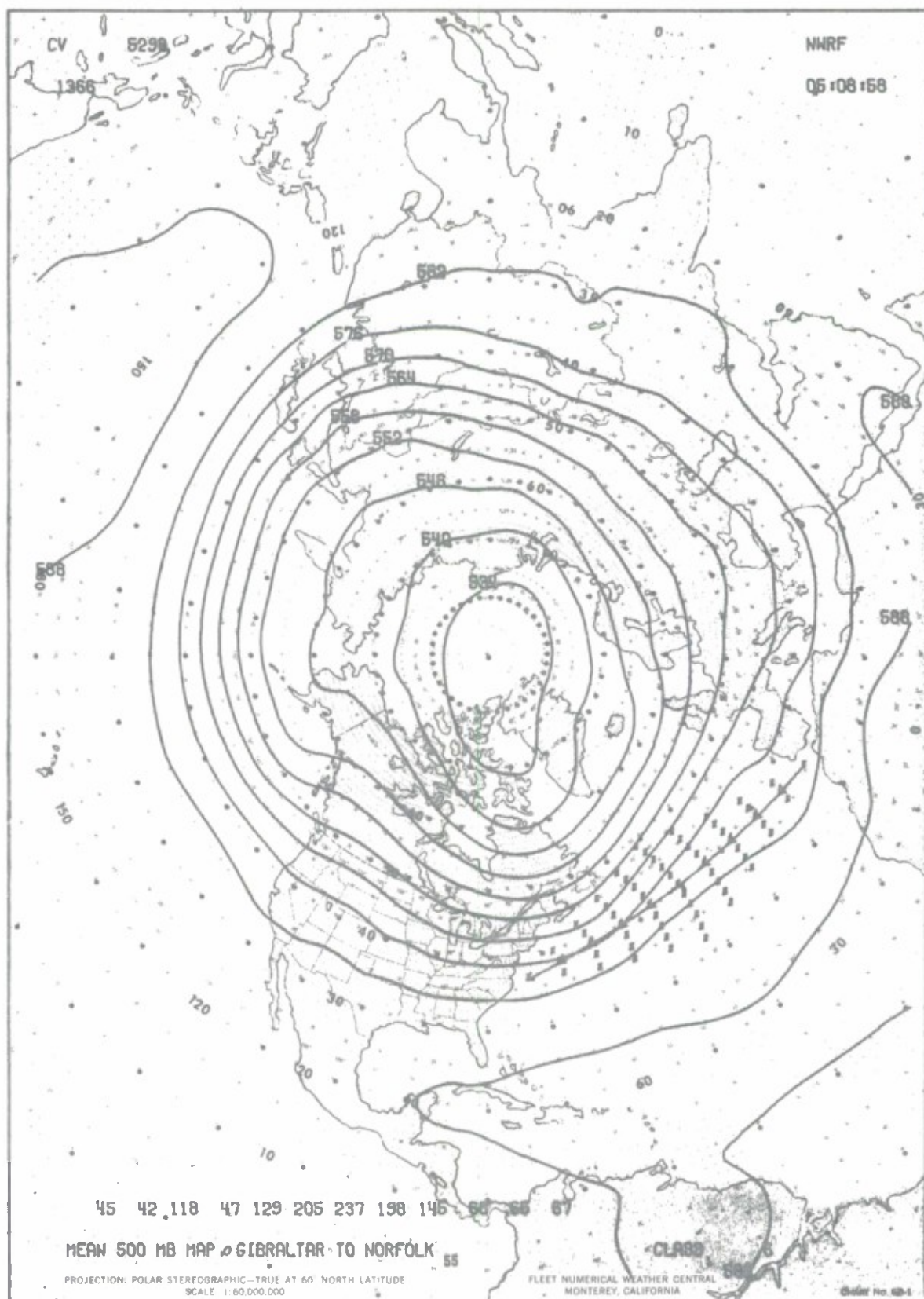


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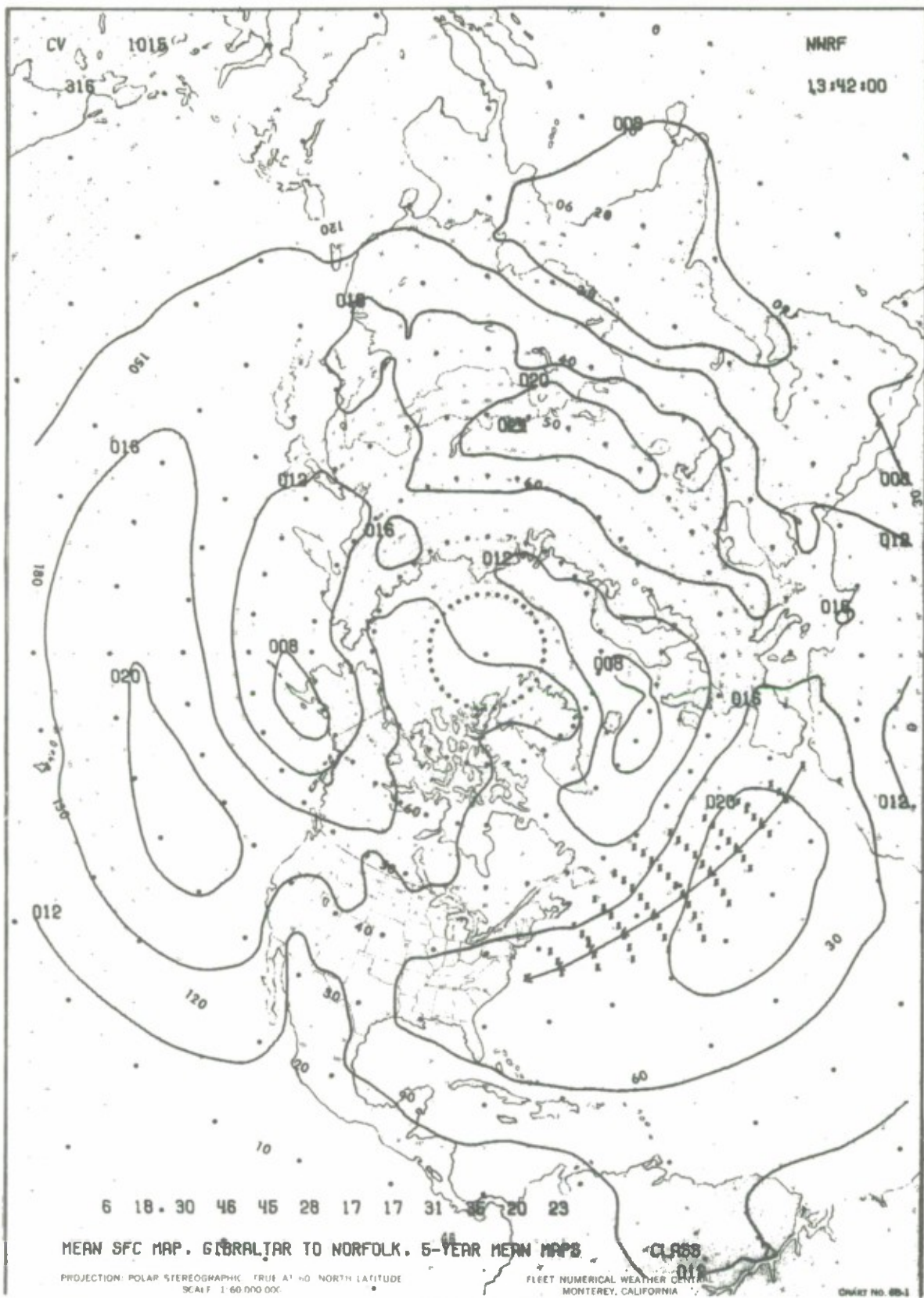


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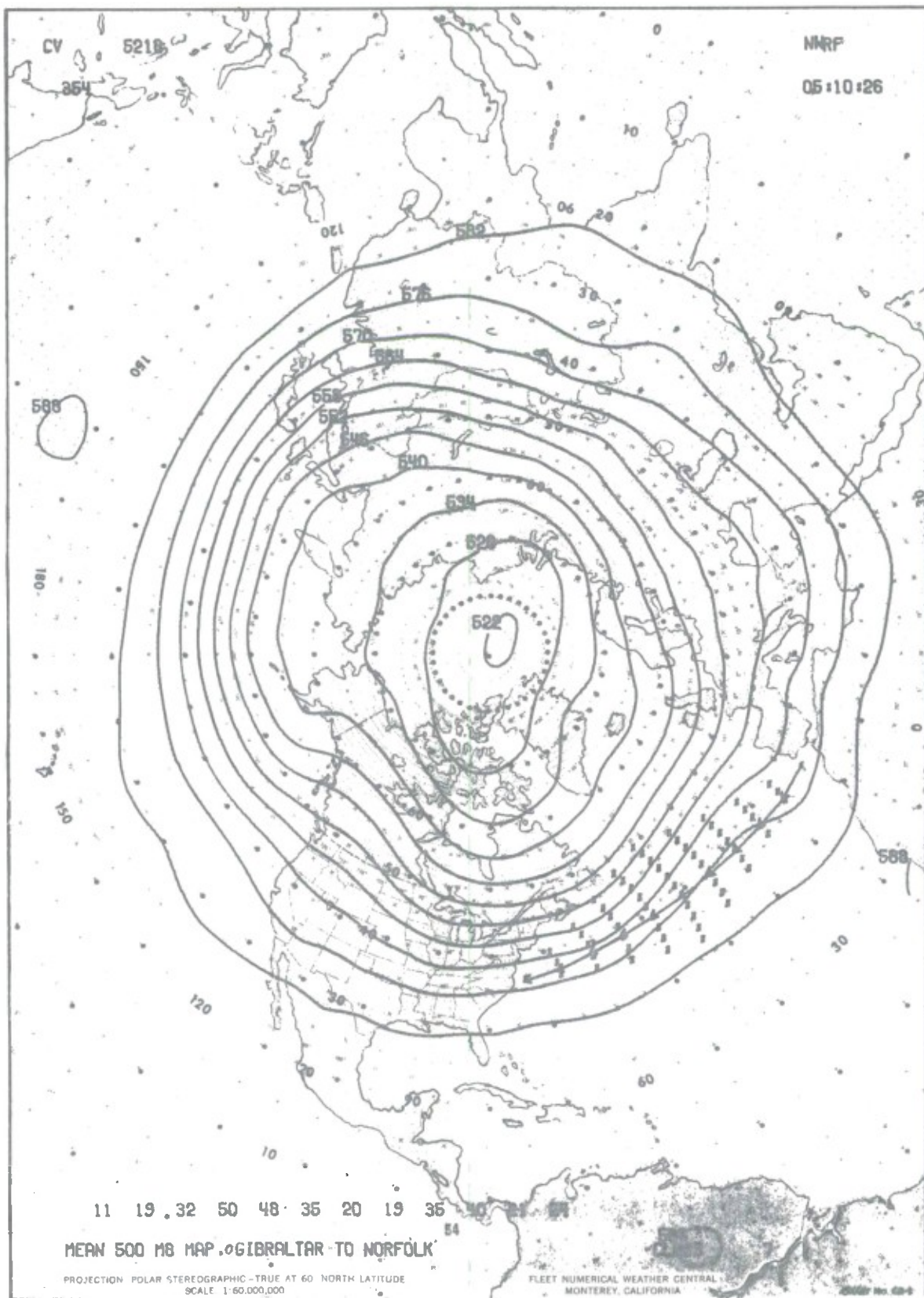


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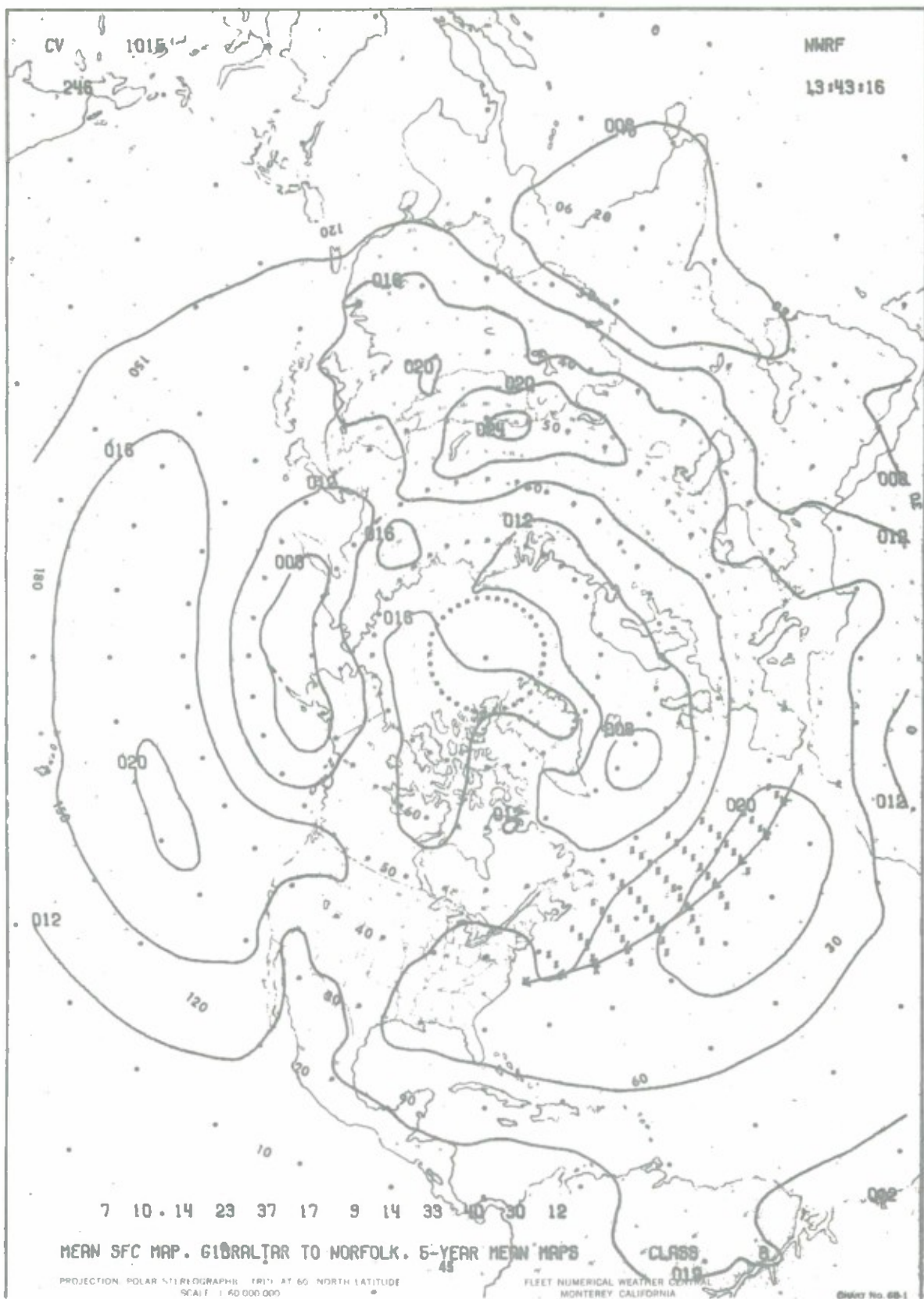


Figure B-8(a).

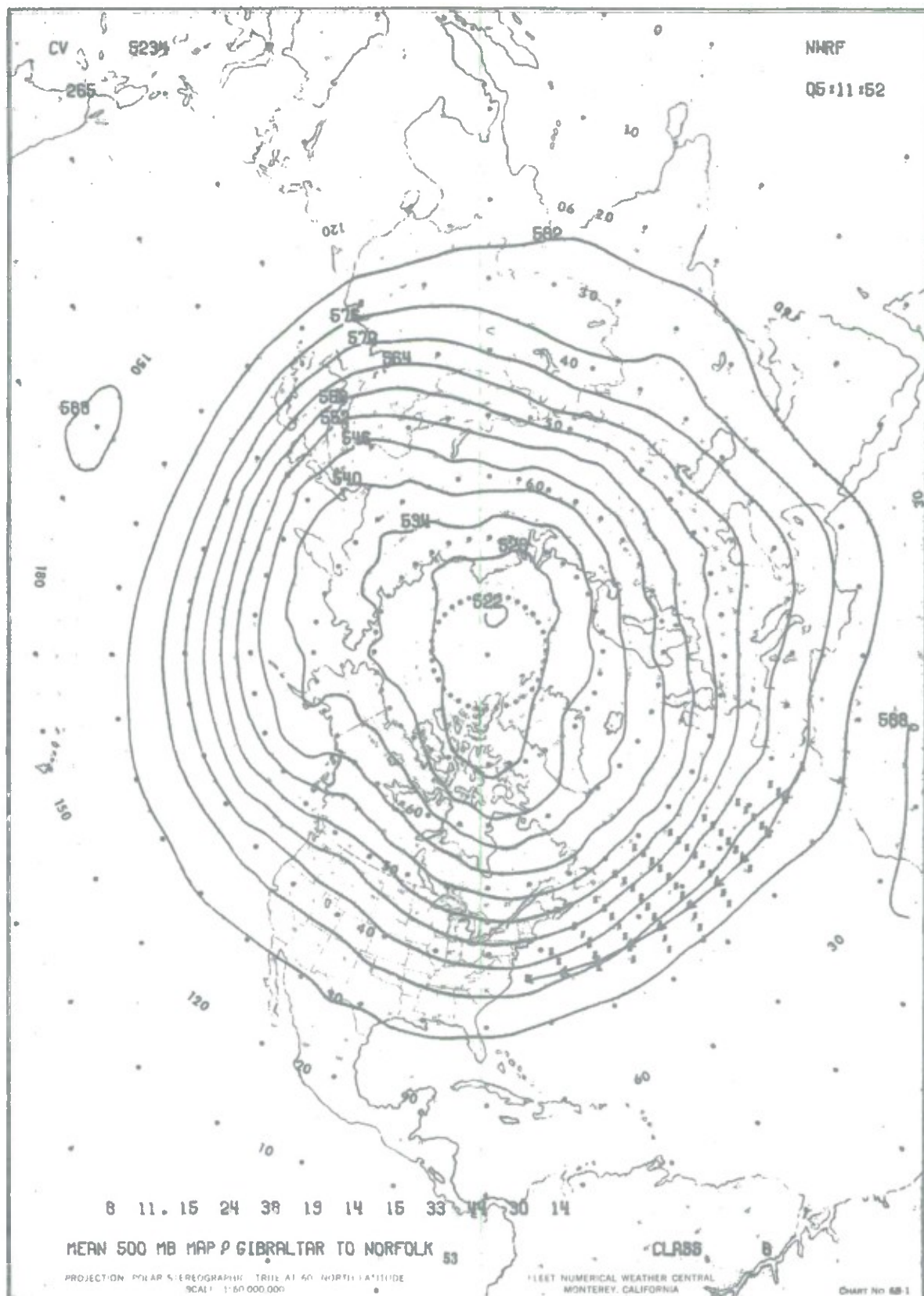


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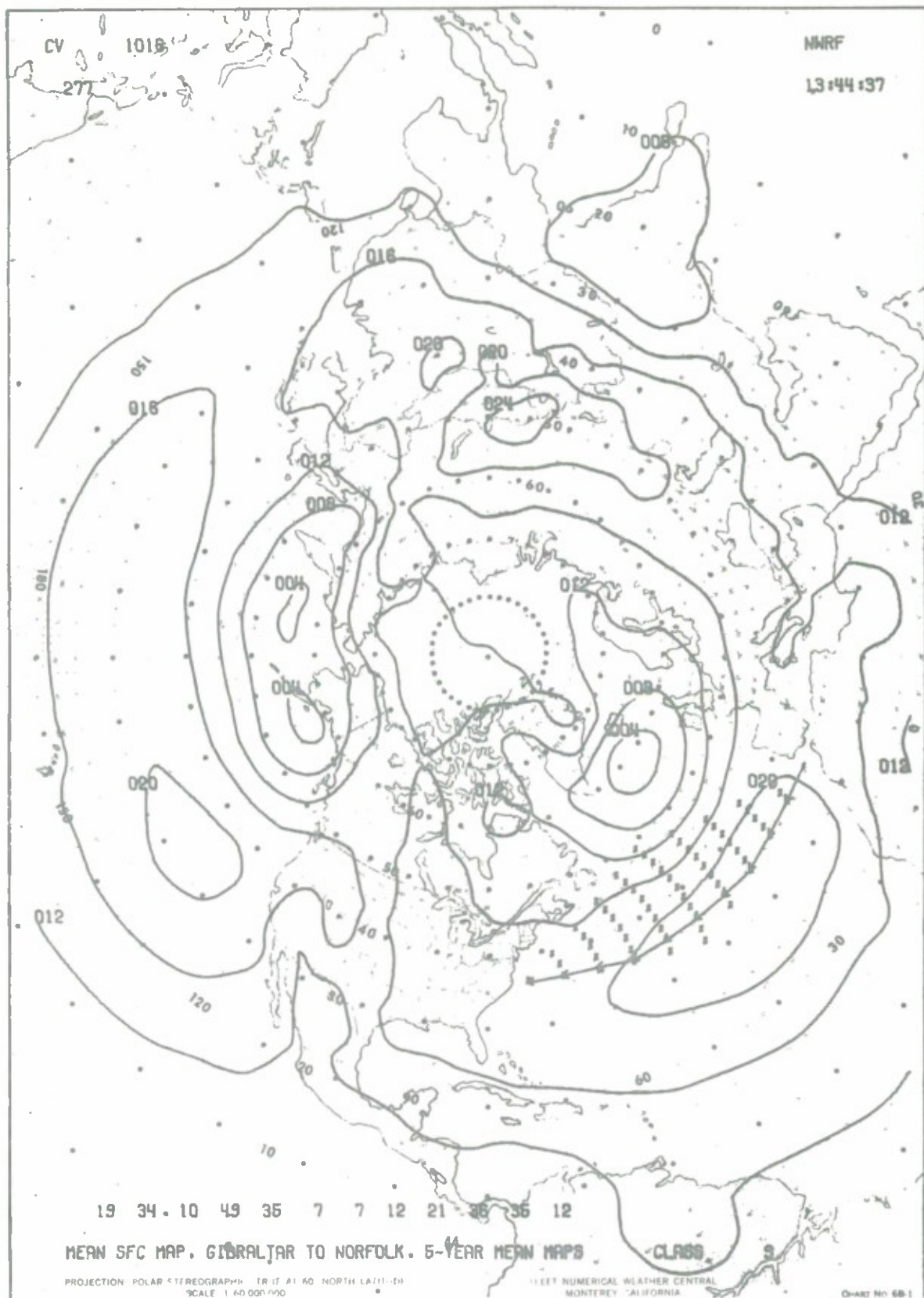
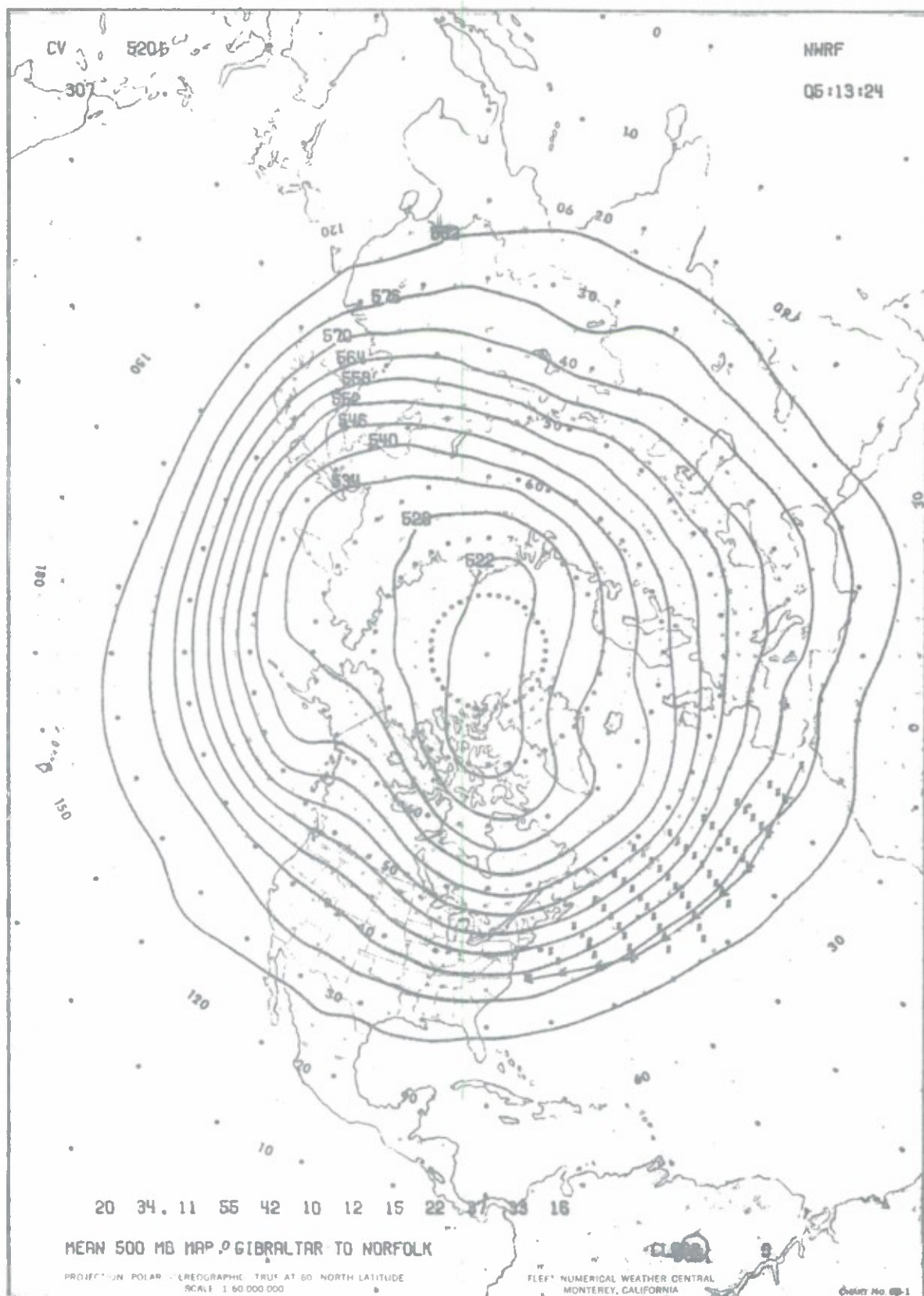


Figure B-9 a).



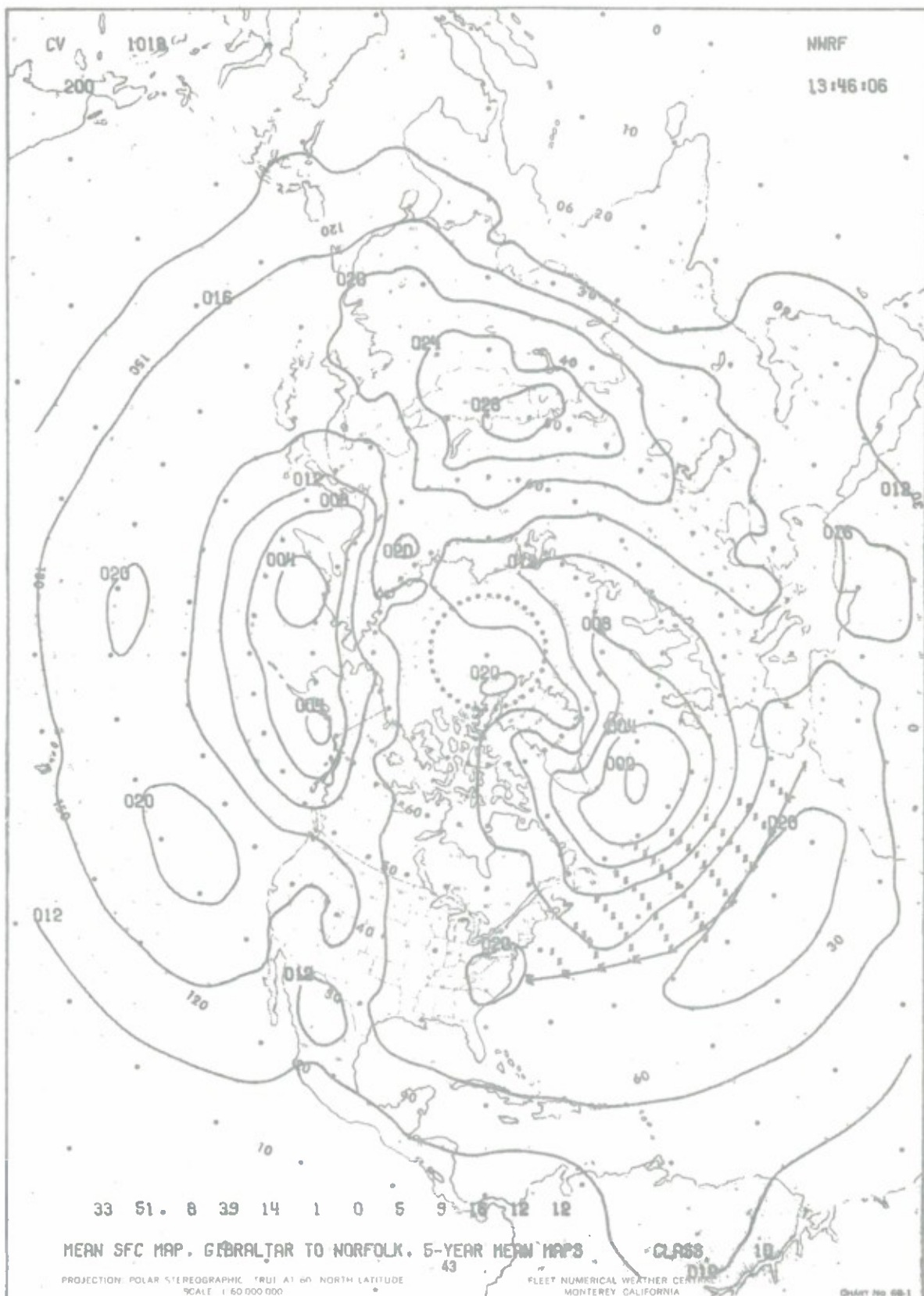


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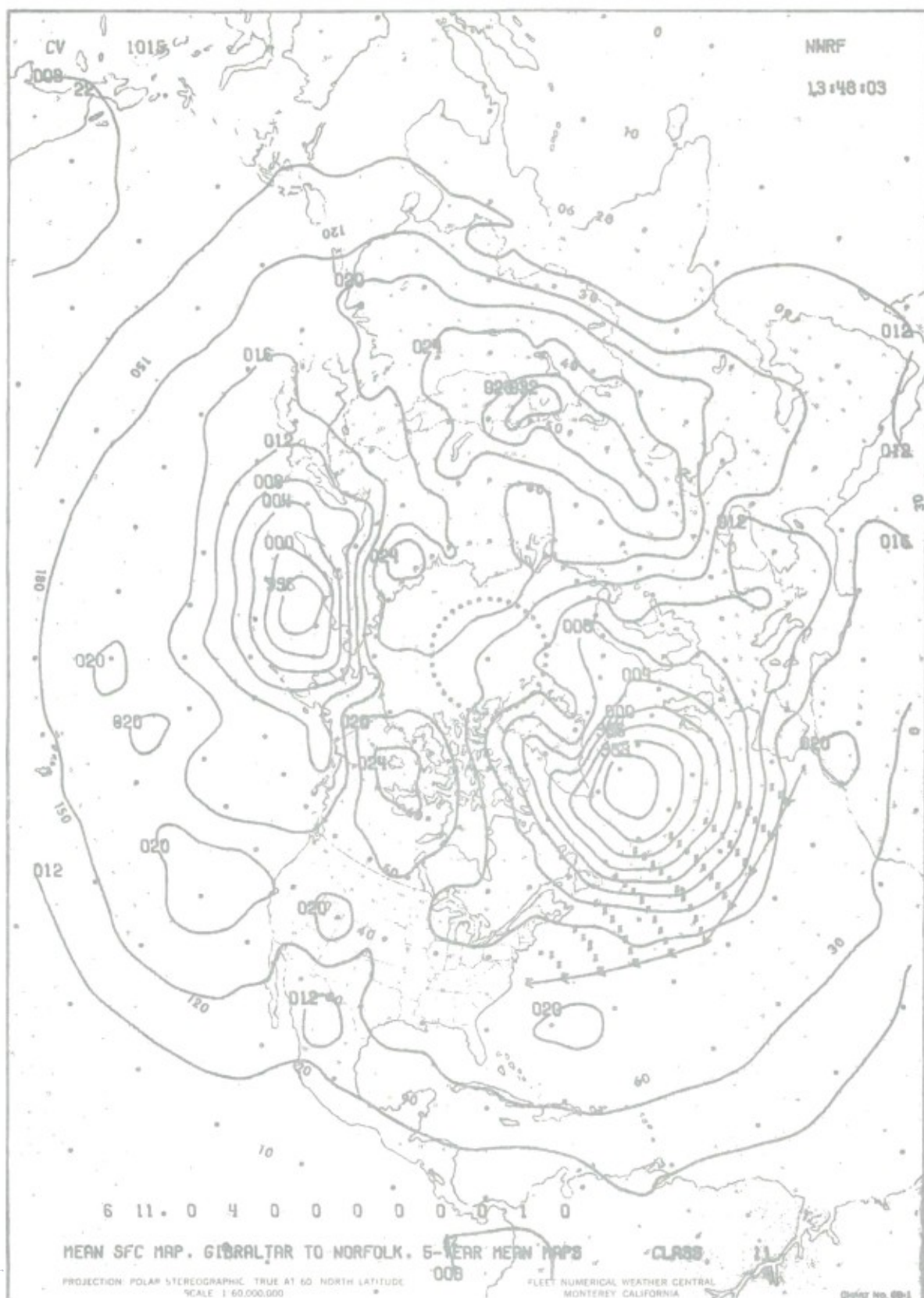


Figure B-11(a).

APPENDIX C

NORFOLK TO BISHOP ROCK

15-KNOT VESSEL

FIGURE C-1	Class 1
FIGURE C-2	Class 2
FIGURE C-3	Class 3
FIGURE C-4	Class 4
FIGURE C-5	Class 5
FIGURE C-6	Class 6
FIGURE C-7	Class 7

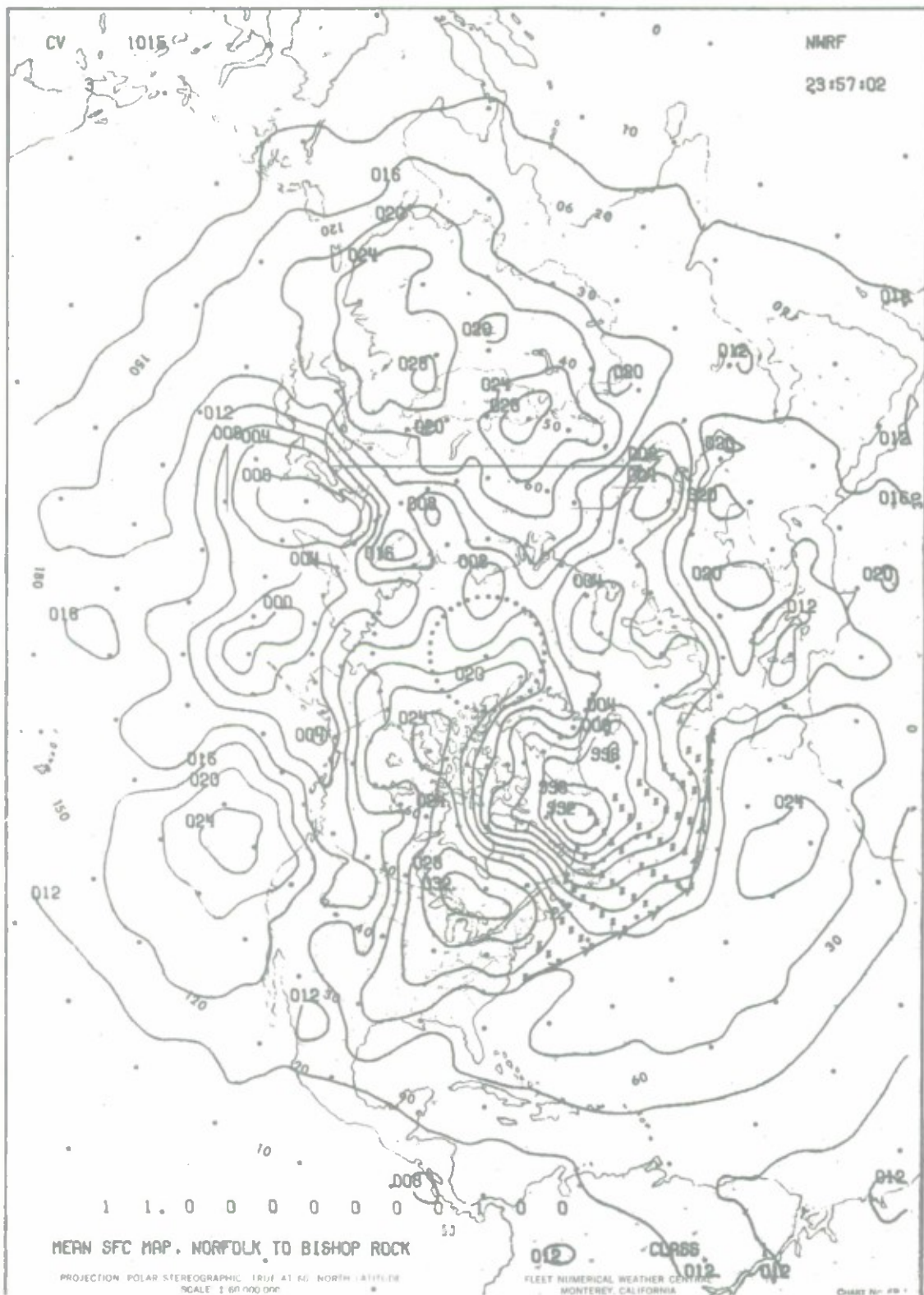
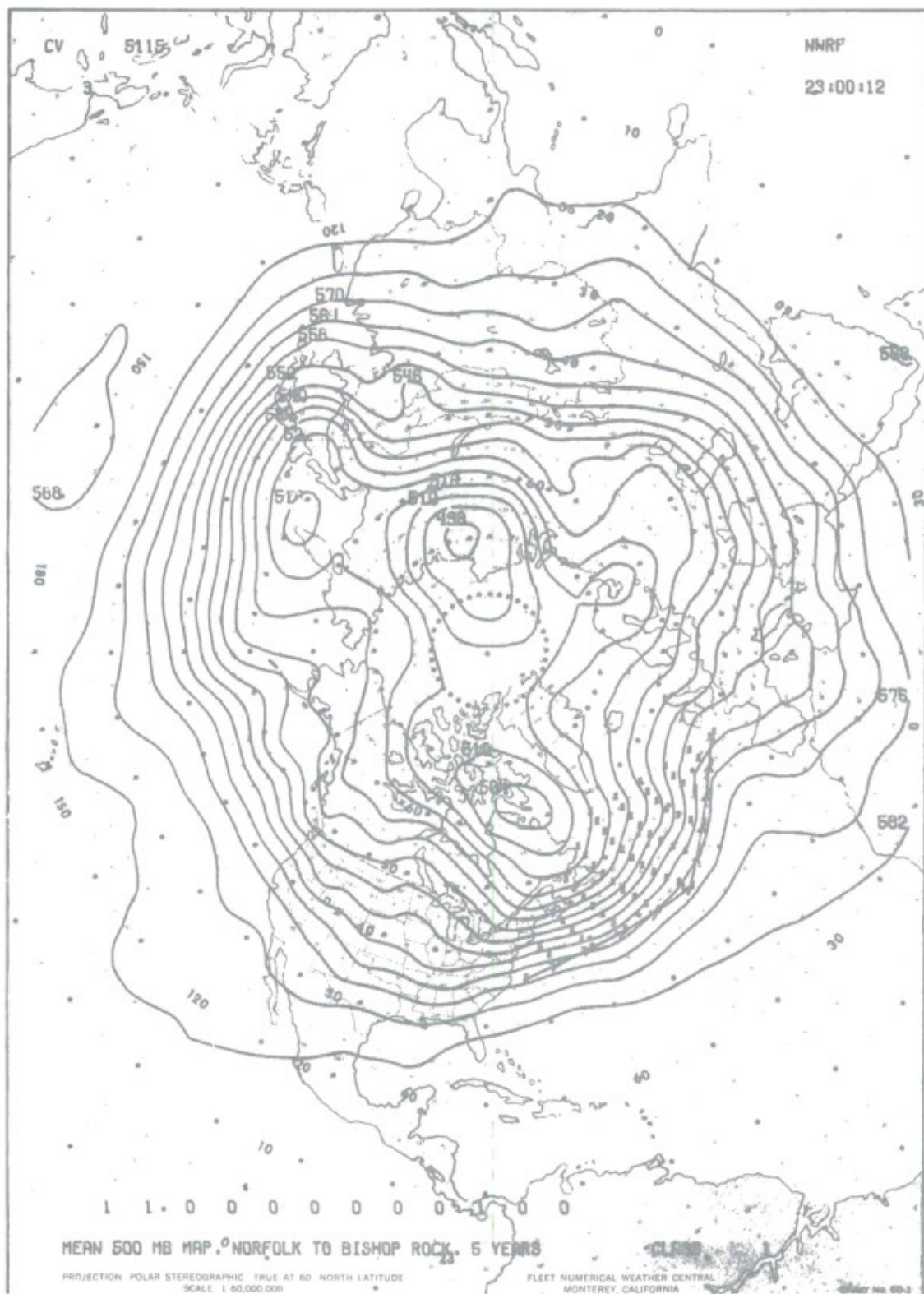


Figure C-1(a).



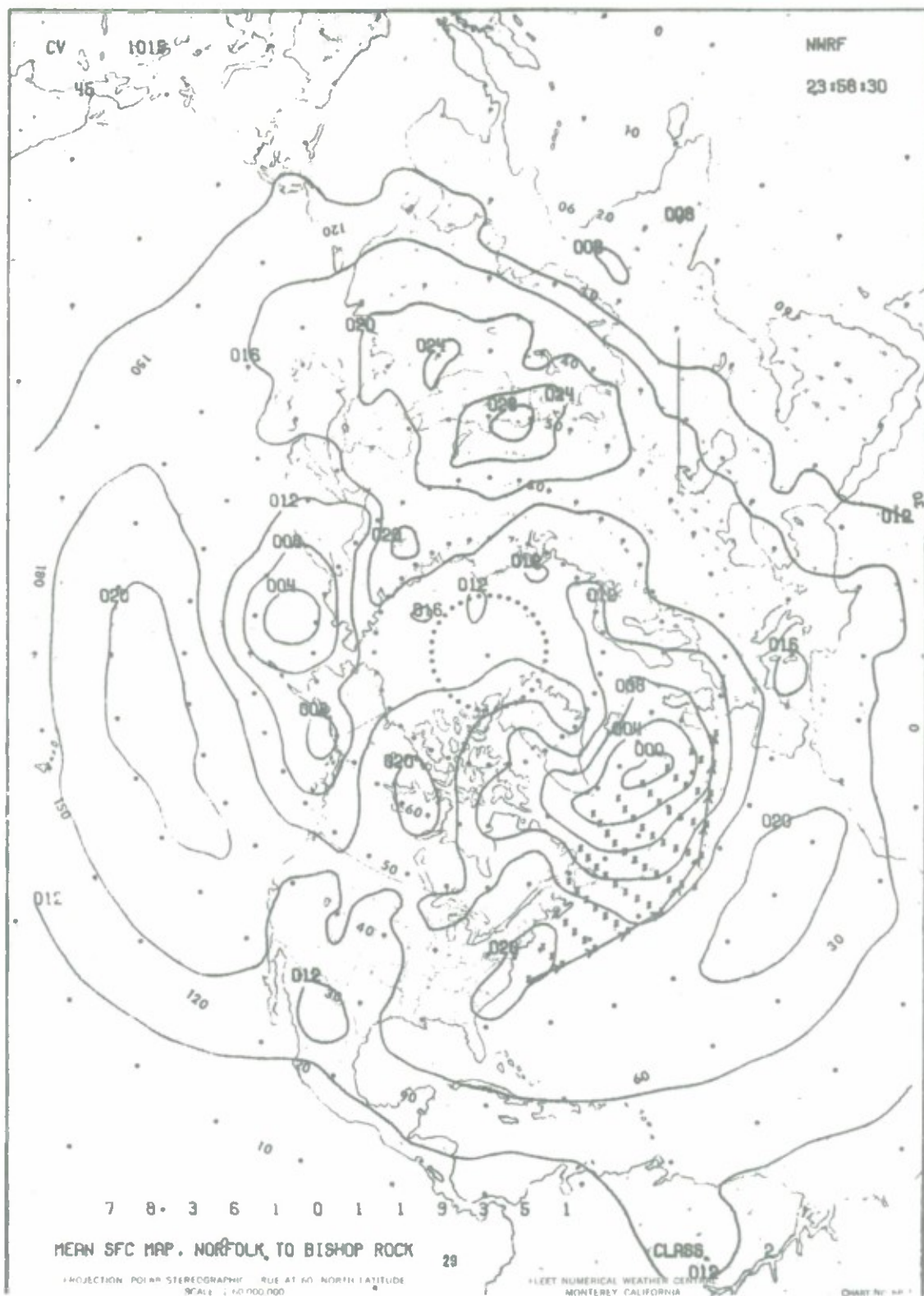


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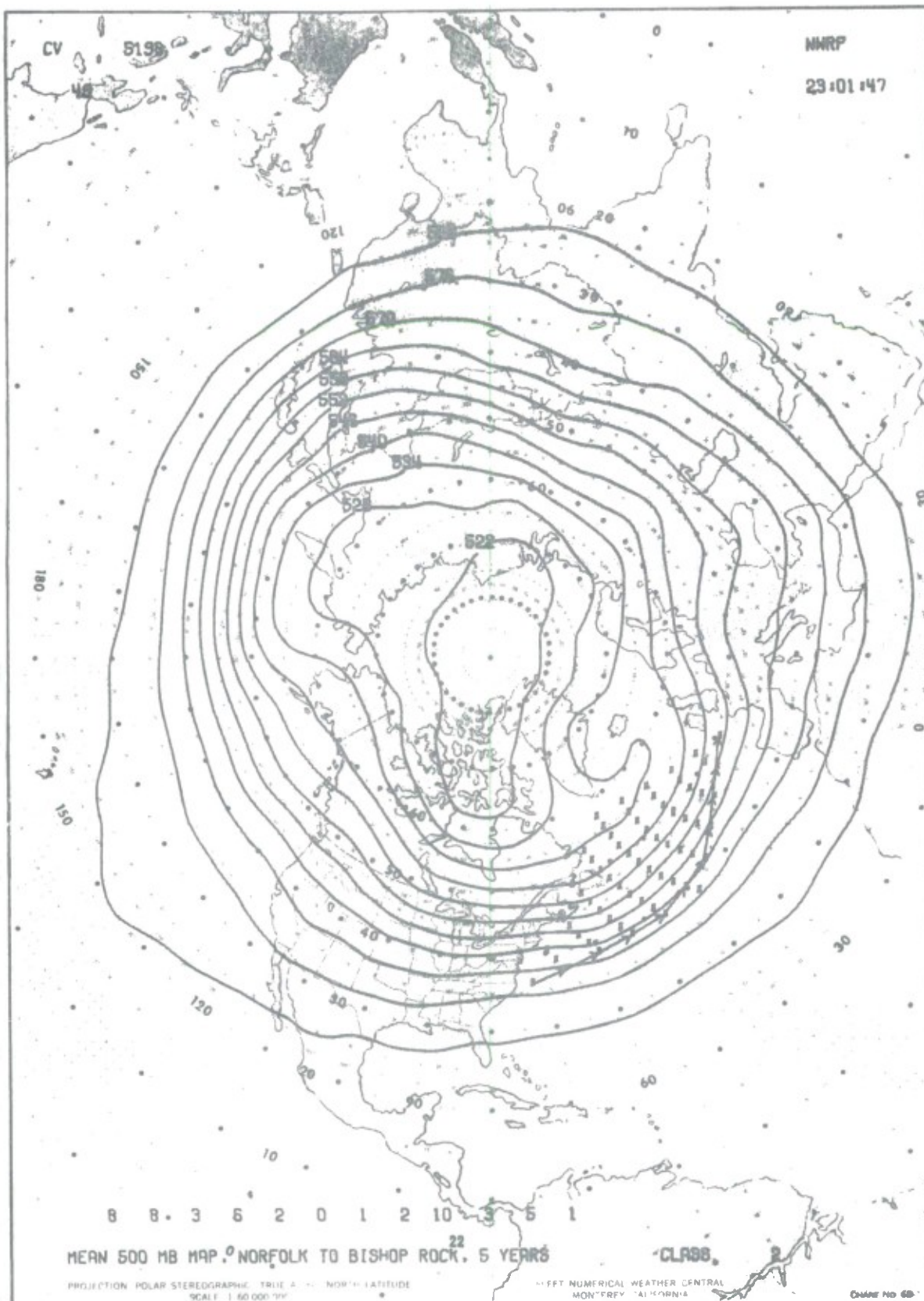


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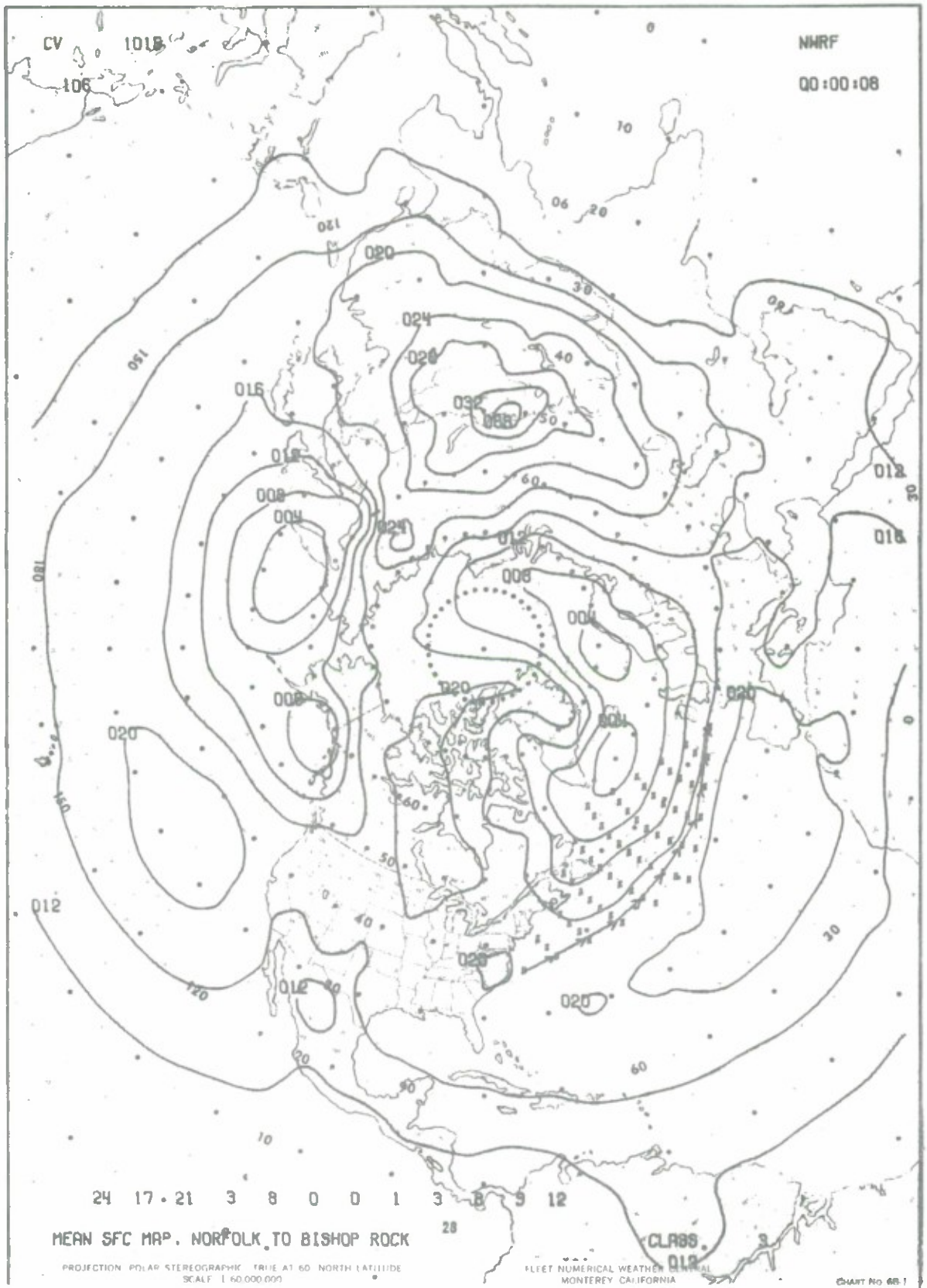


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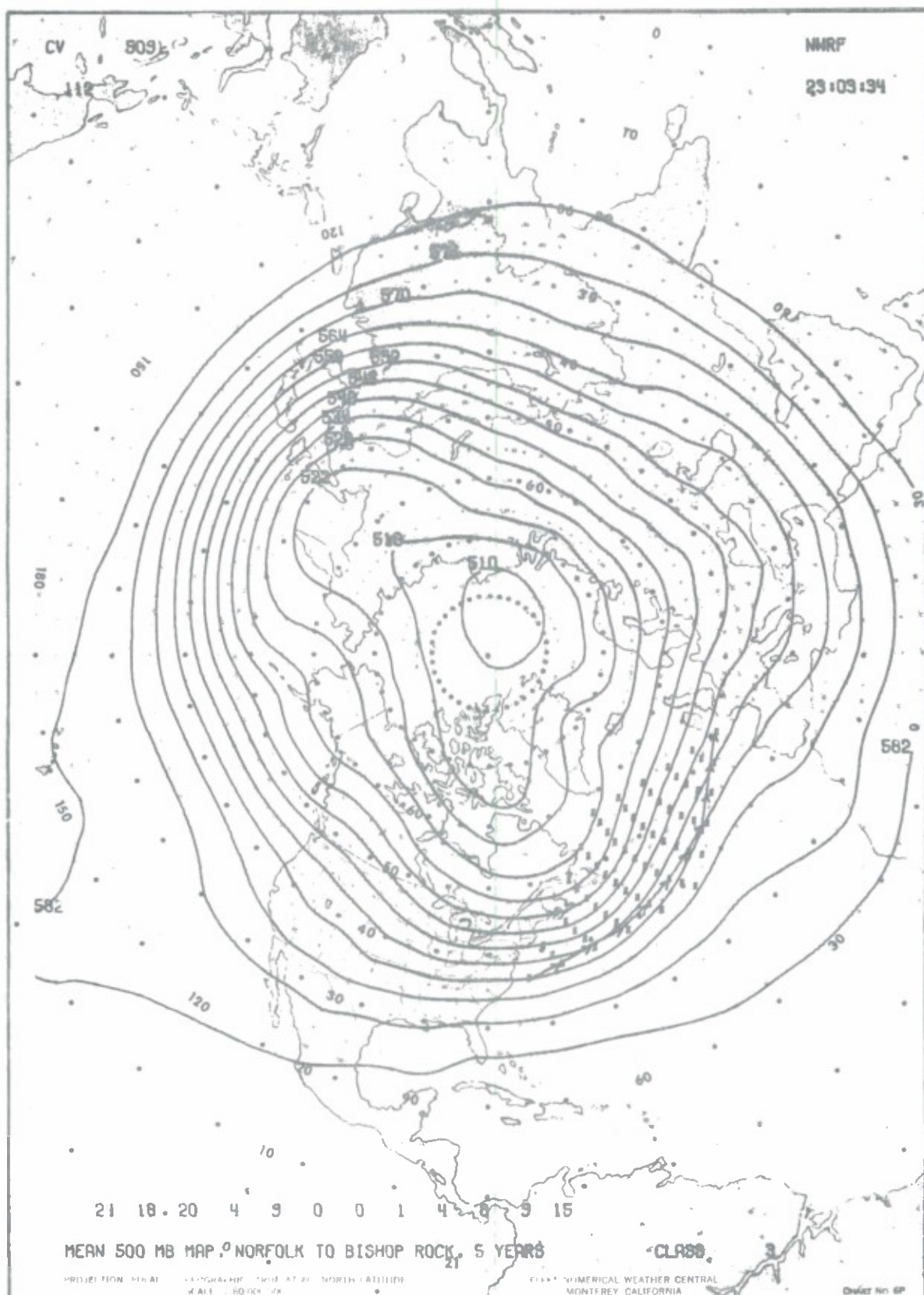


Figure C-3(b)

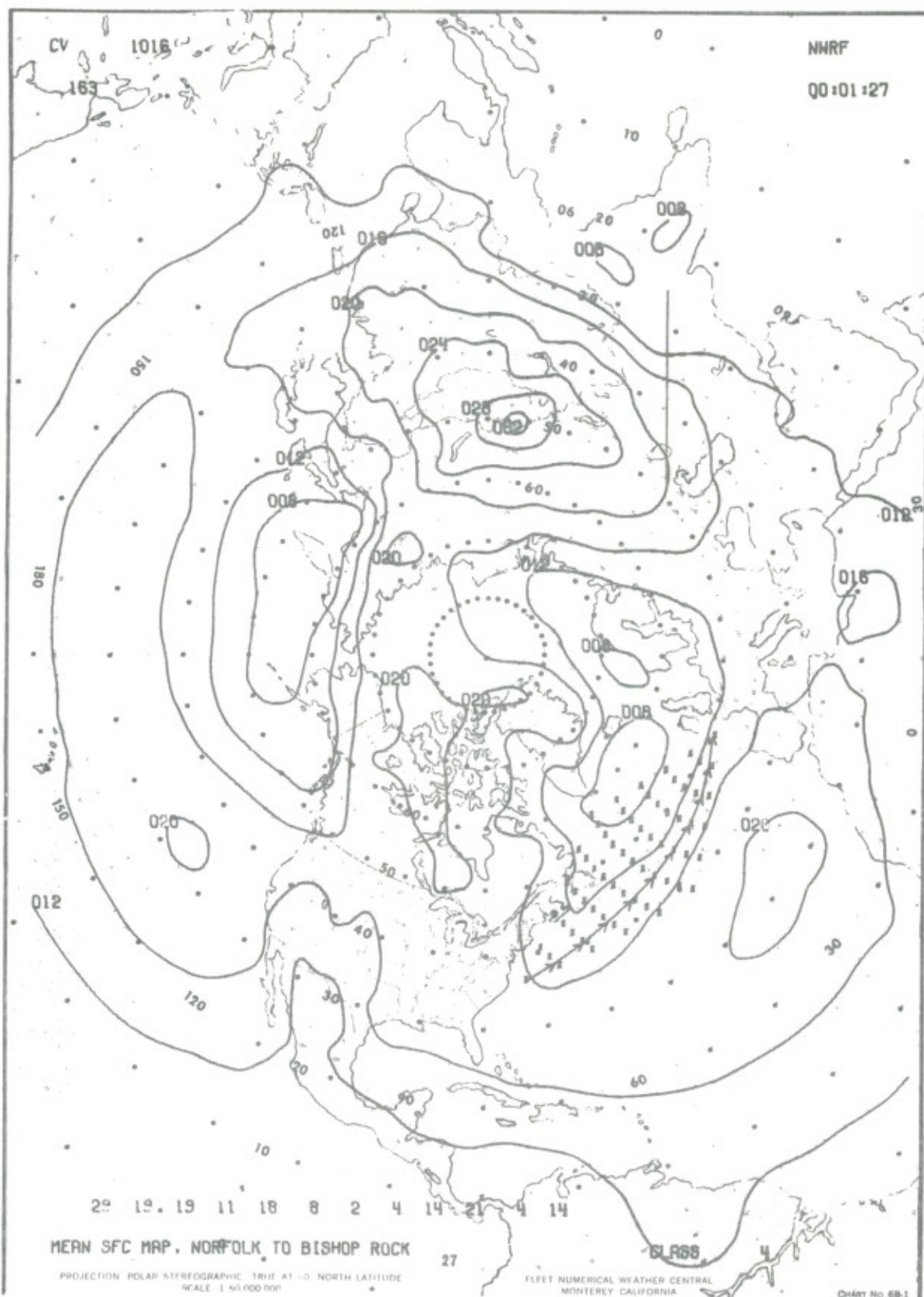


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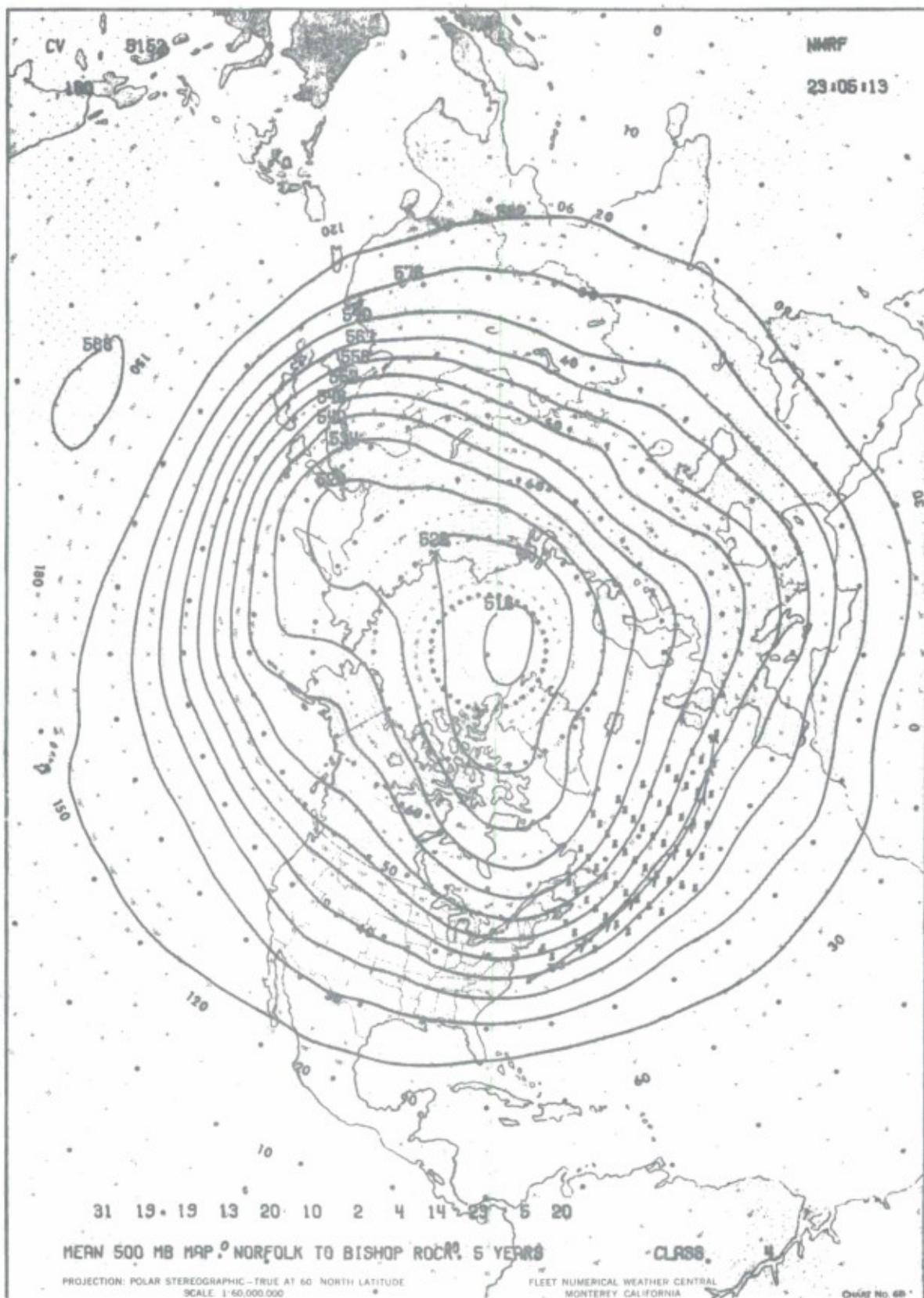


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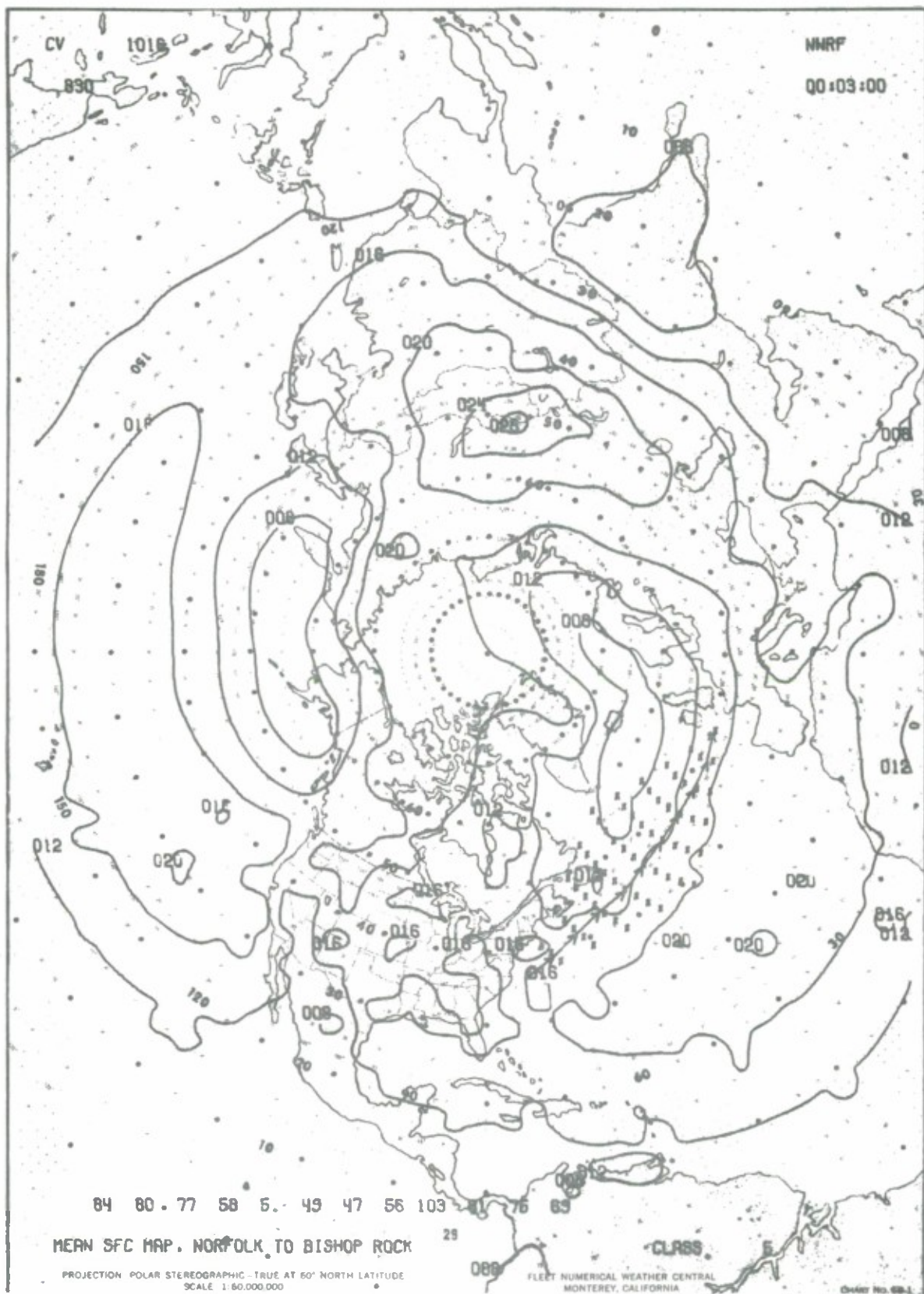


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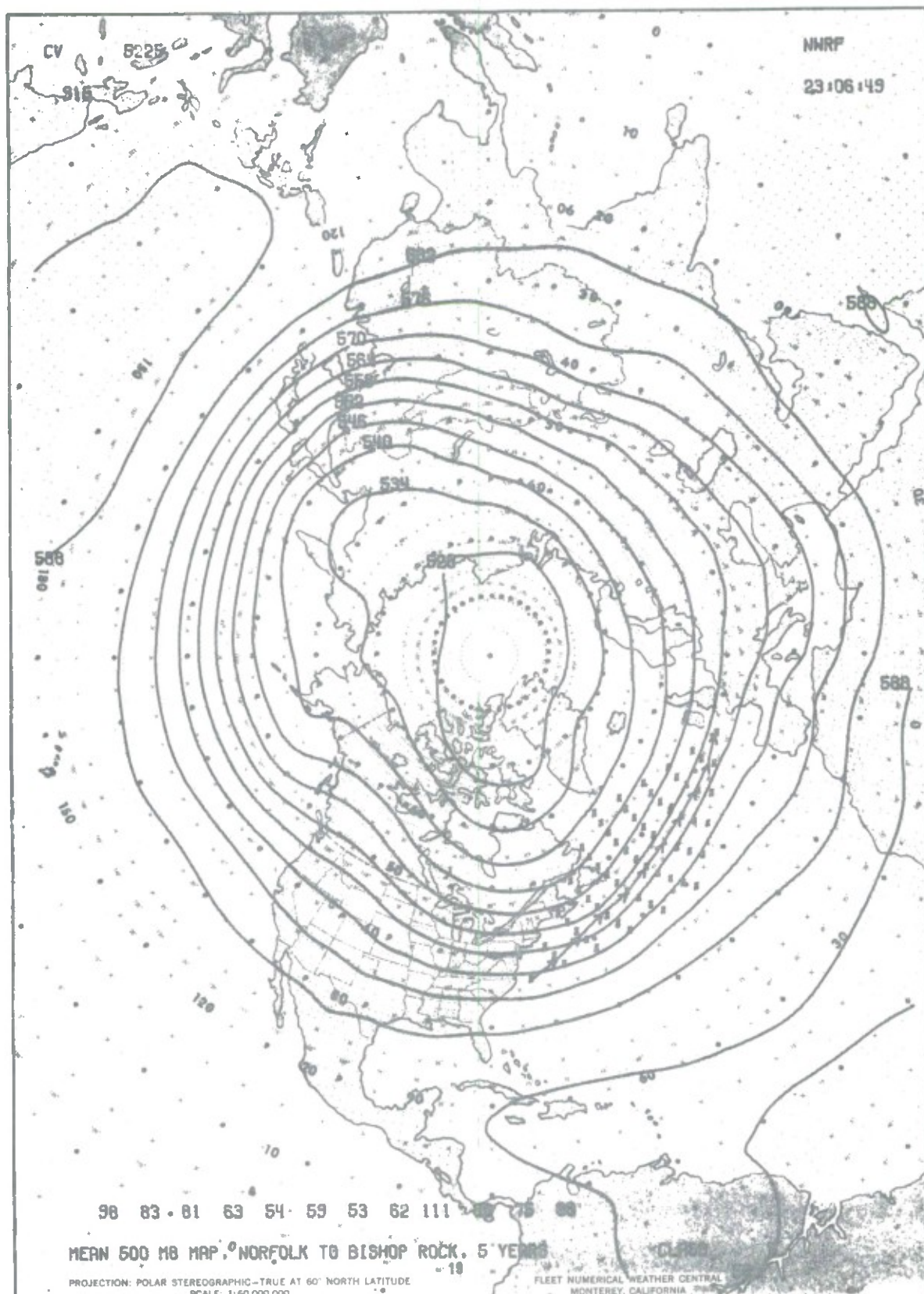


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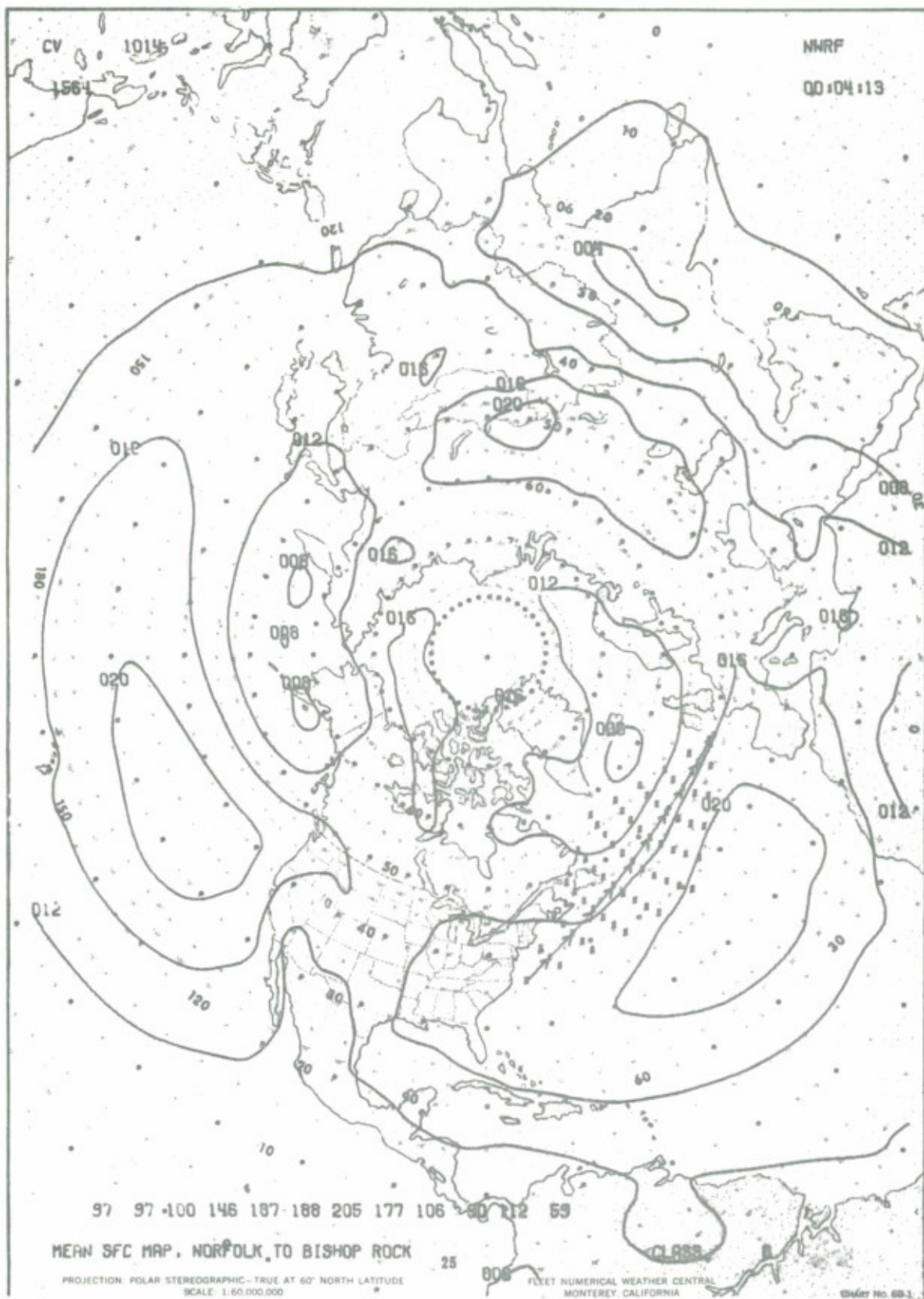
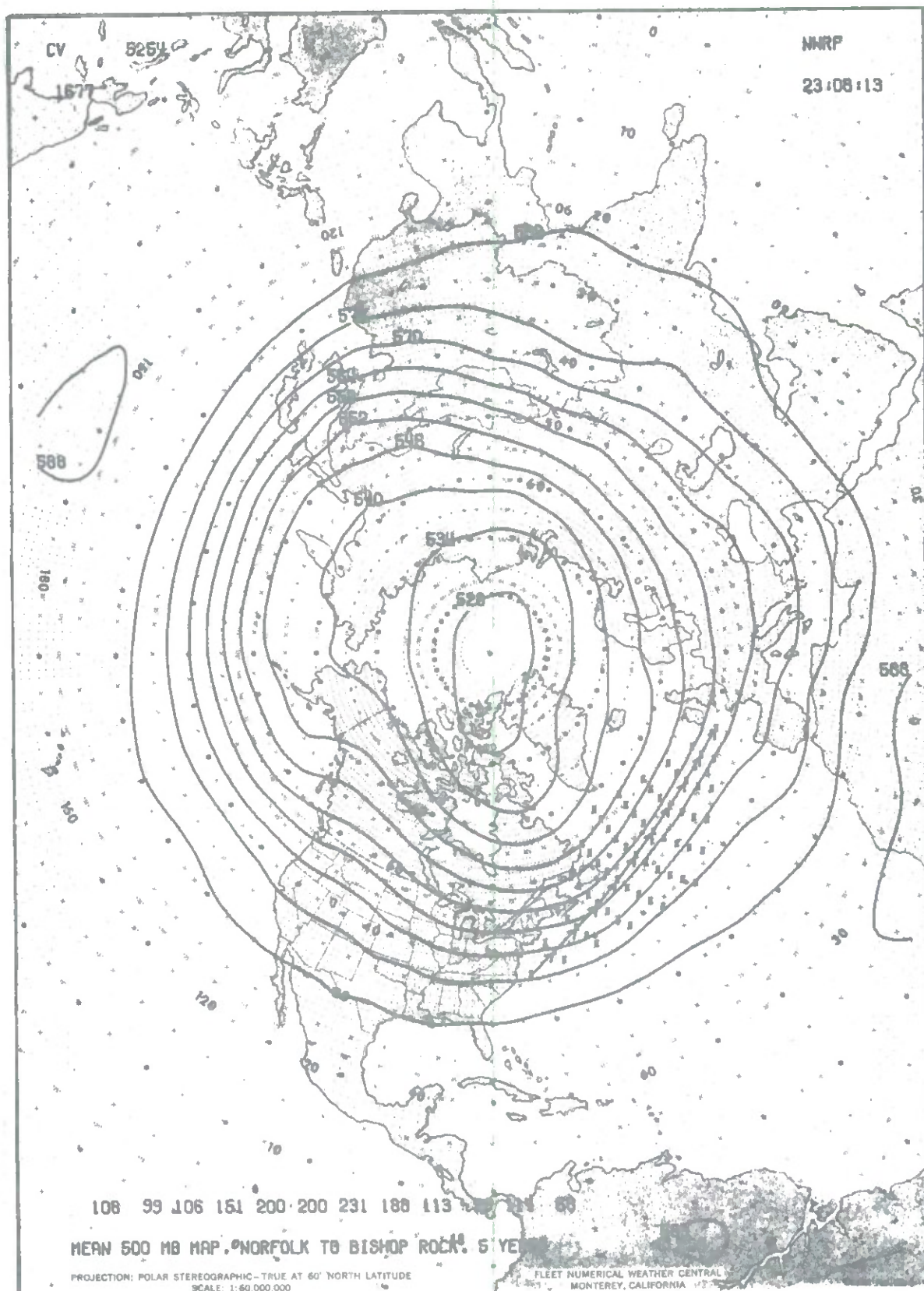
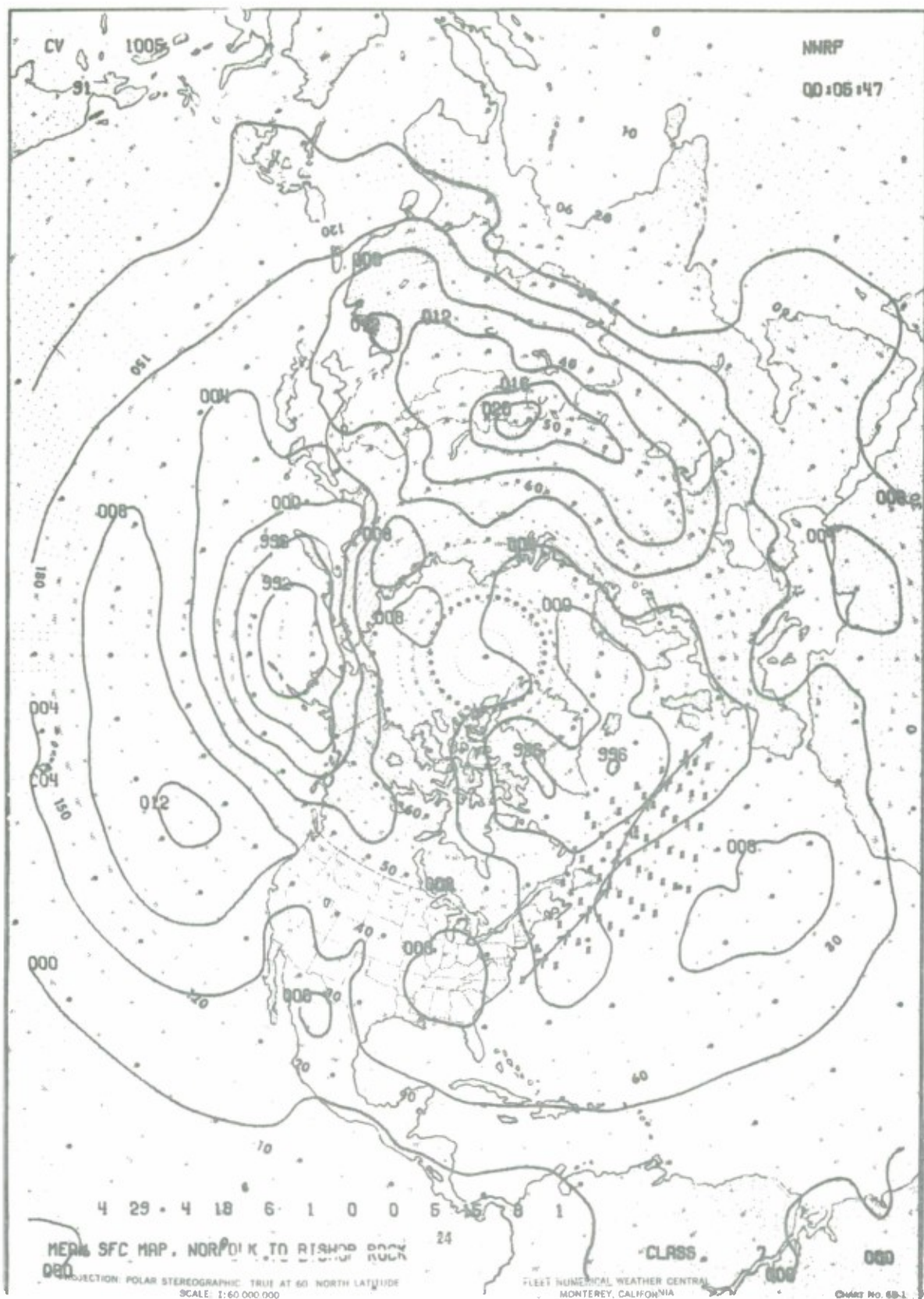


Figure C-6(a).





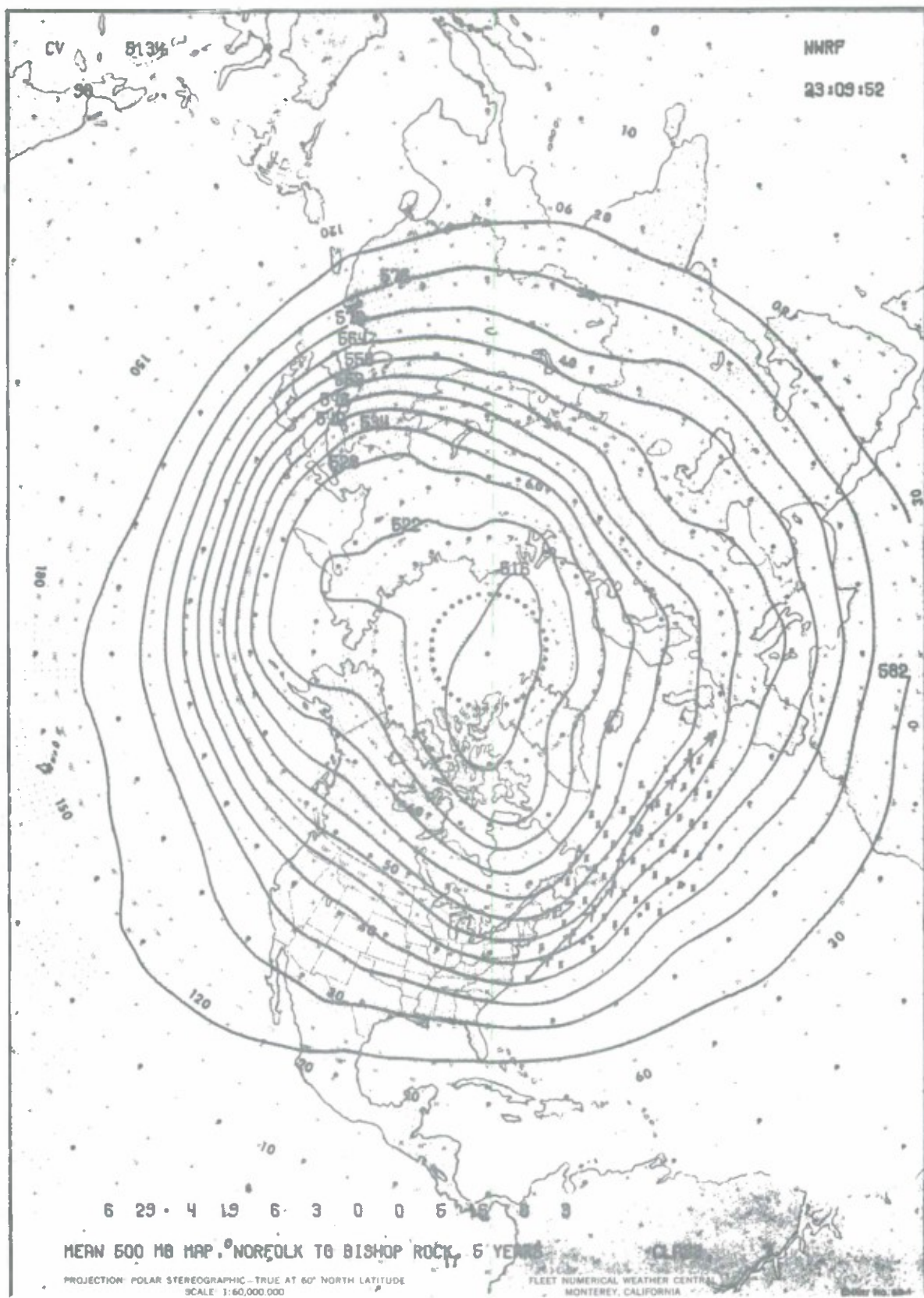


Figure C-7(b).

APPENDIX D

NORFOLK TO GIBRALTAR

15-KNOT VESSEL

FIGURE D-1	Class 1
FIGURE D-2	Class 2
FIGURE D-3	Class 3
FIGURE D-4	Class 4
FIGURE D-5	Class 5
FIGURE D-6	Class 6
FIGURE D-7	Class 7
FIGURE D-8	Class 8
FIGURE D-9	Class 9
FIGURE D-10	Class 10
FIGURE D-11	Class 11

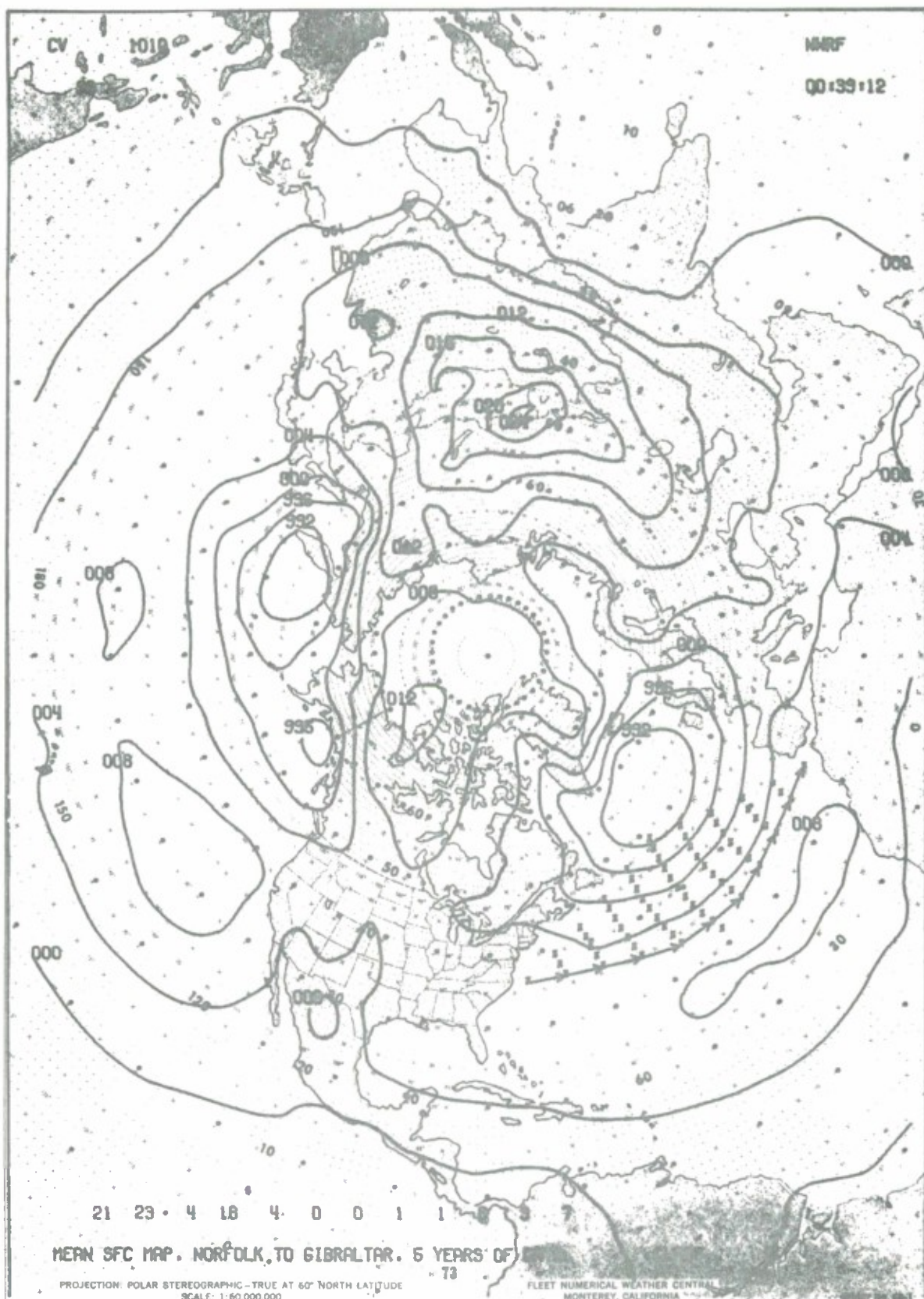


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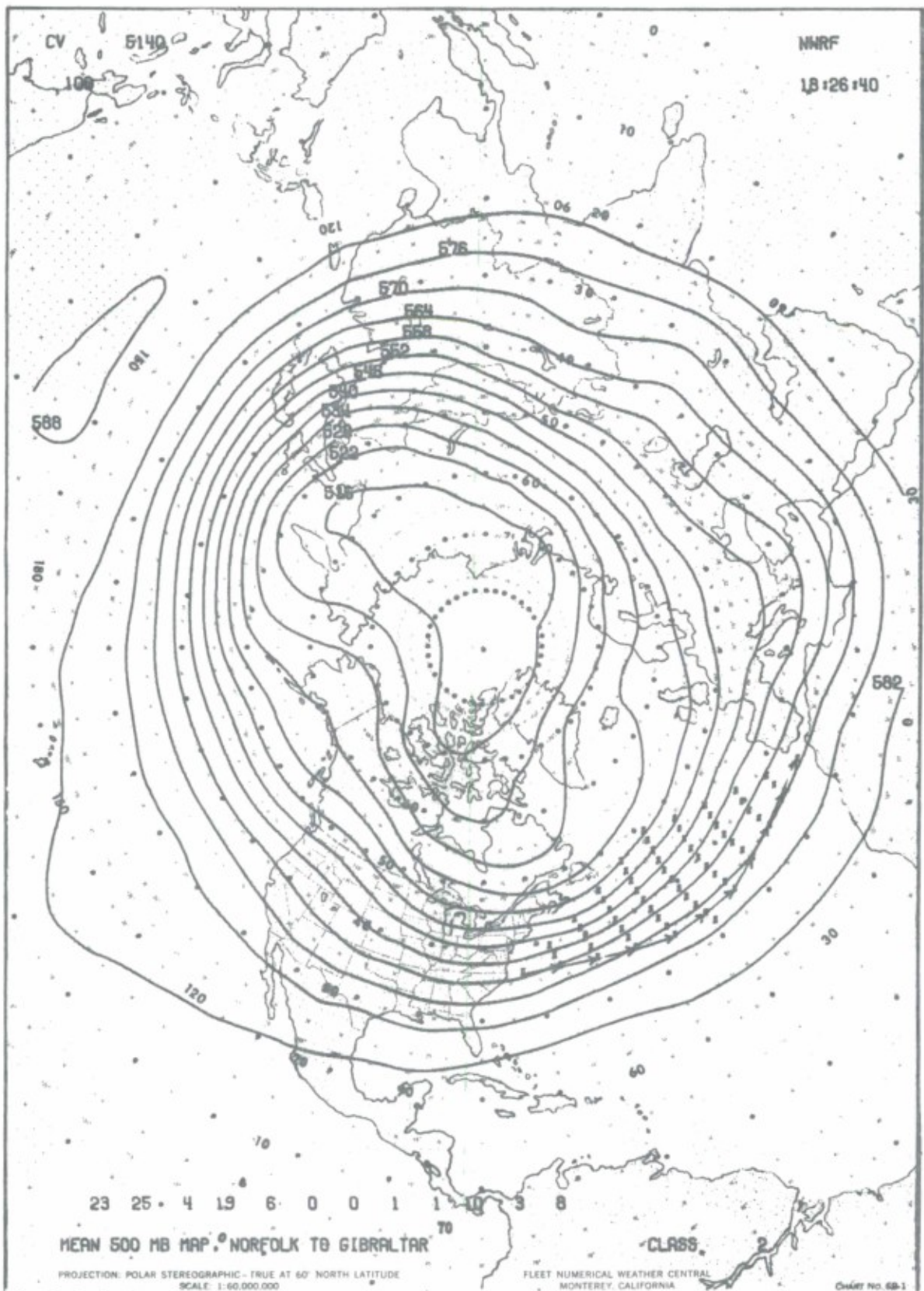


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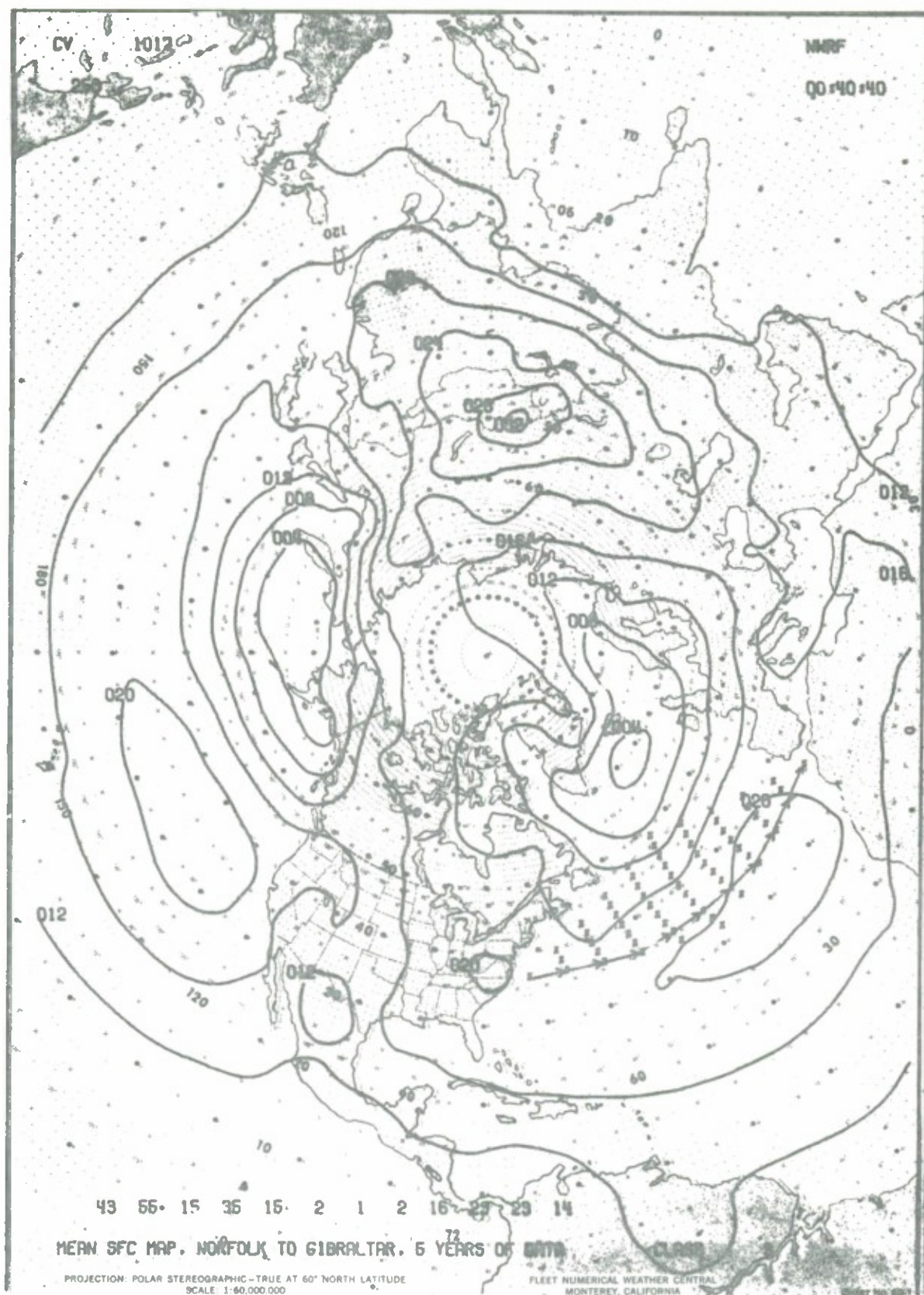


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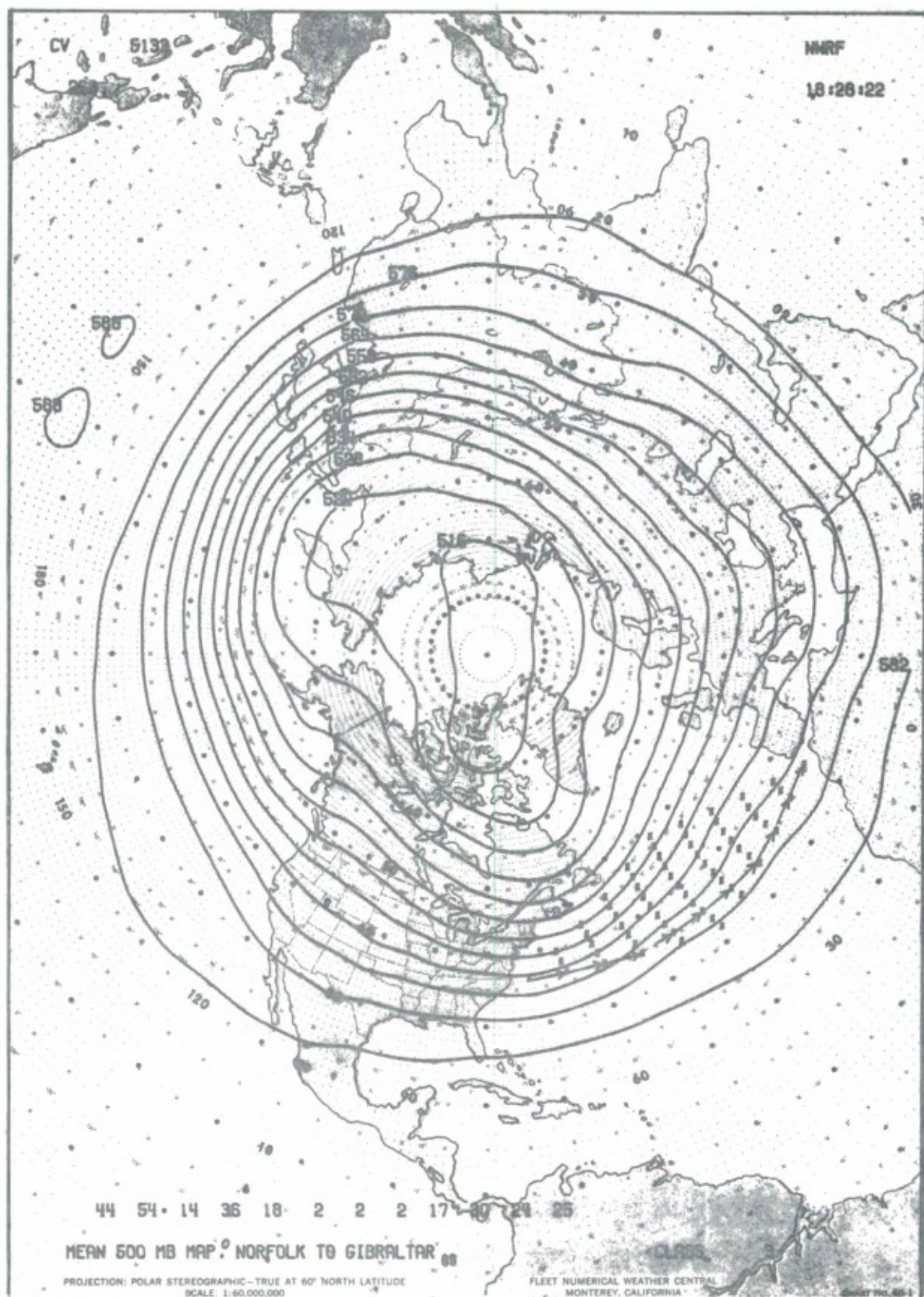


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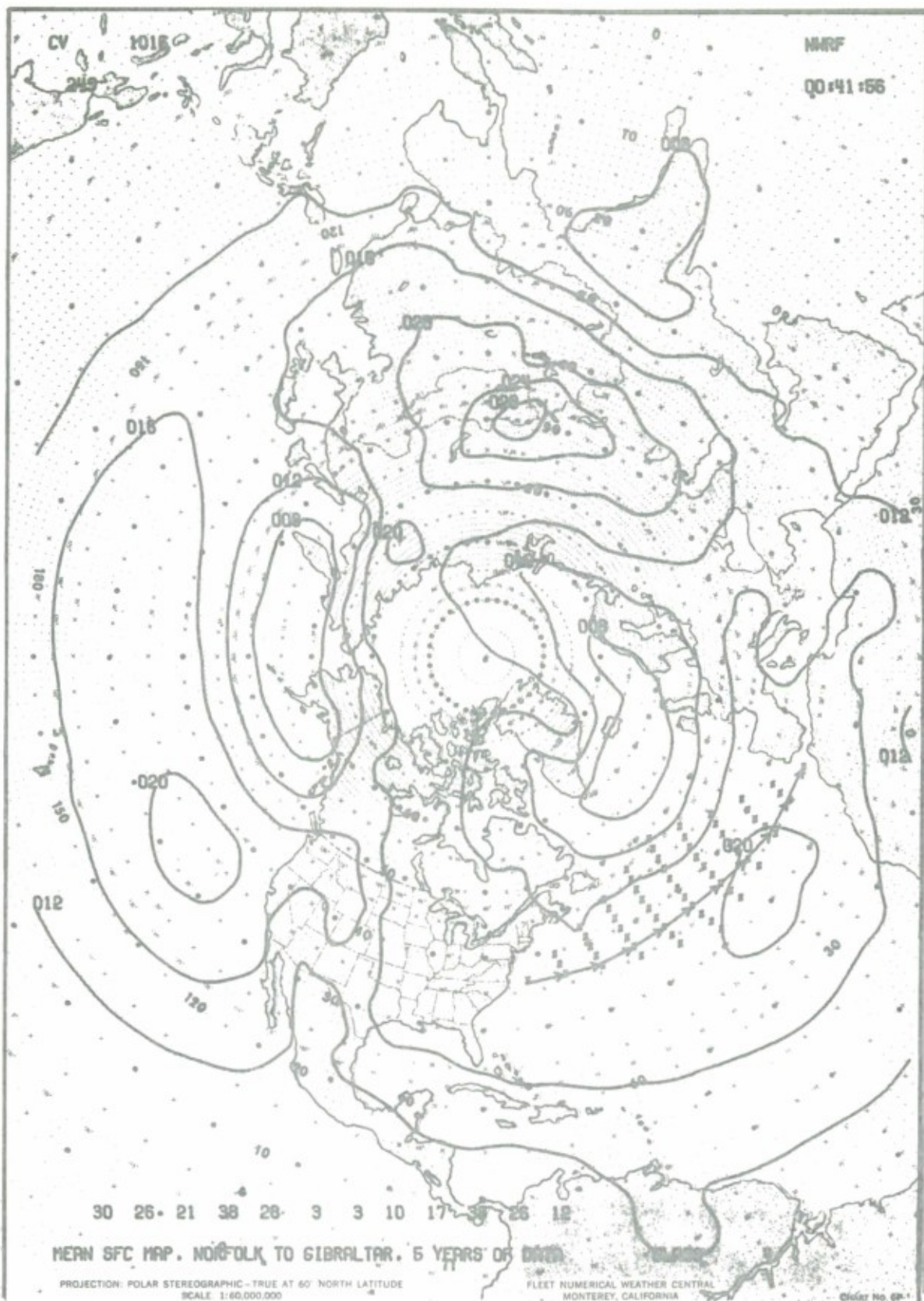


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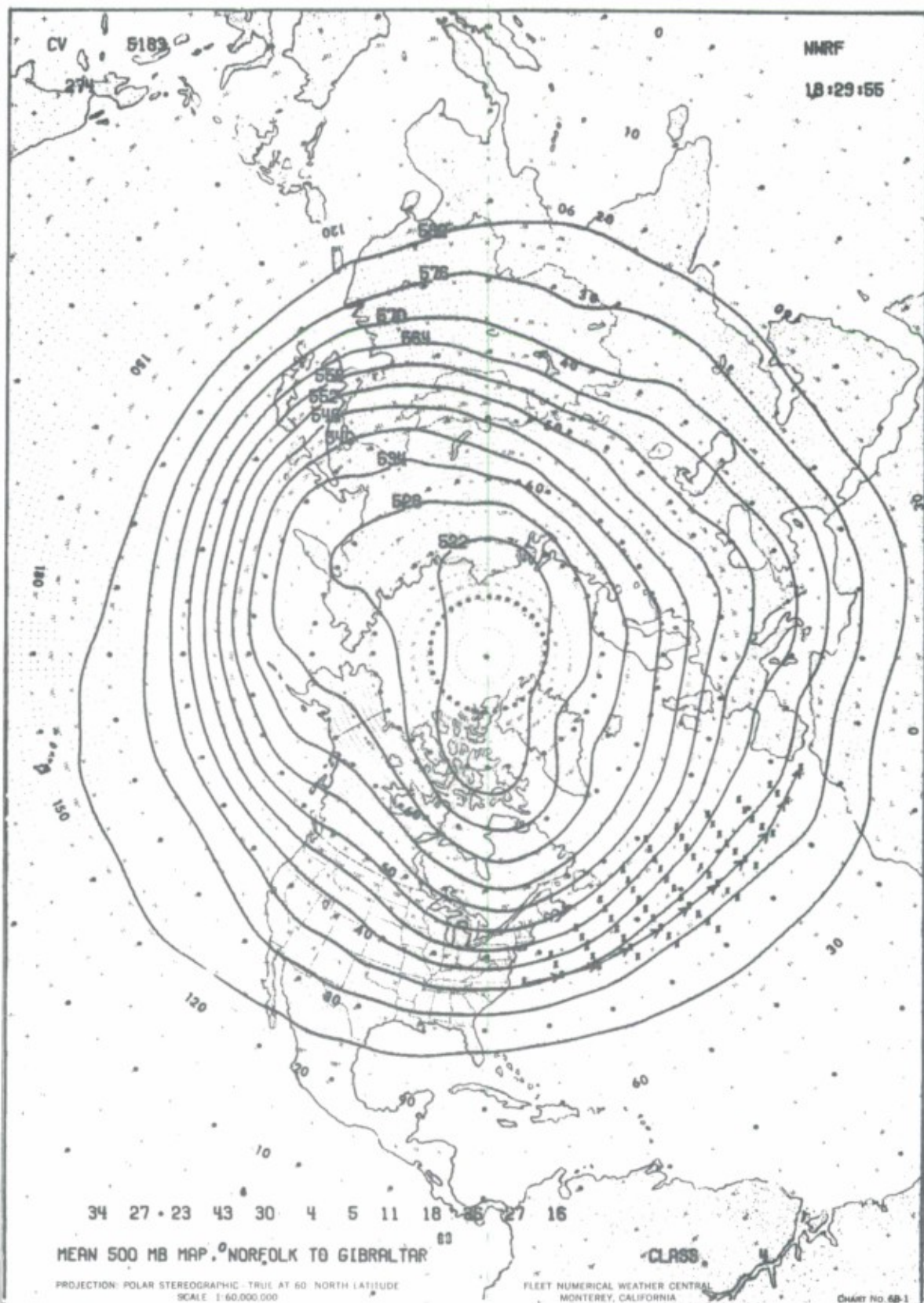


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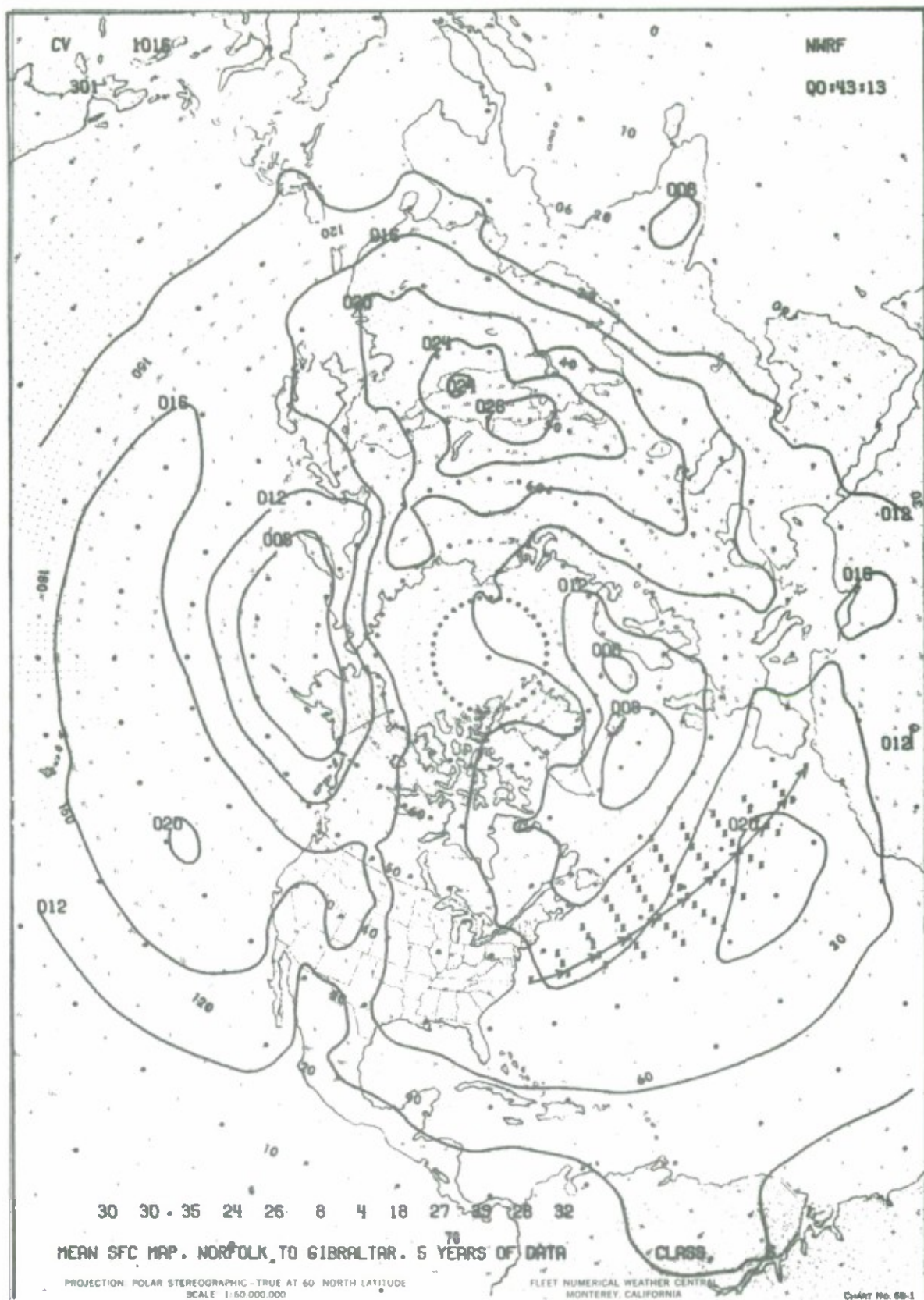


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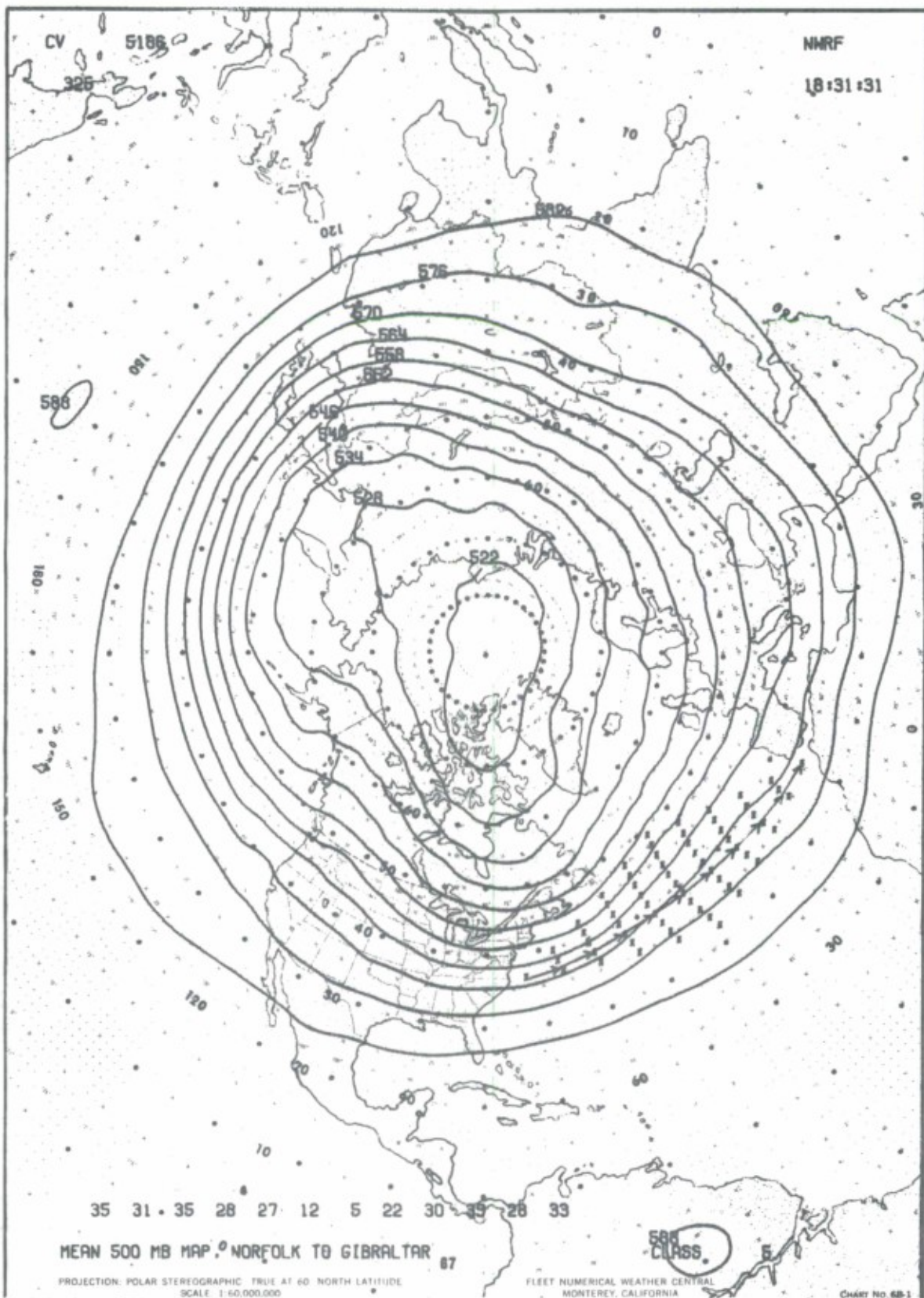


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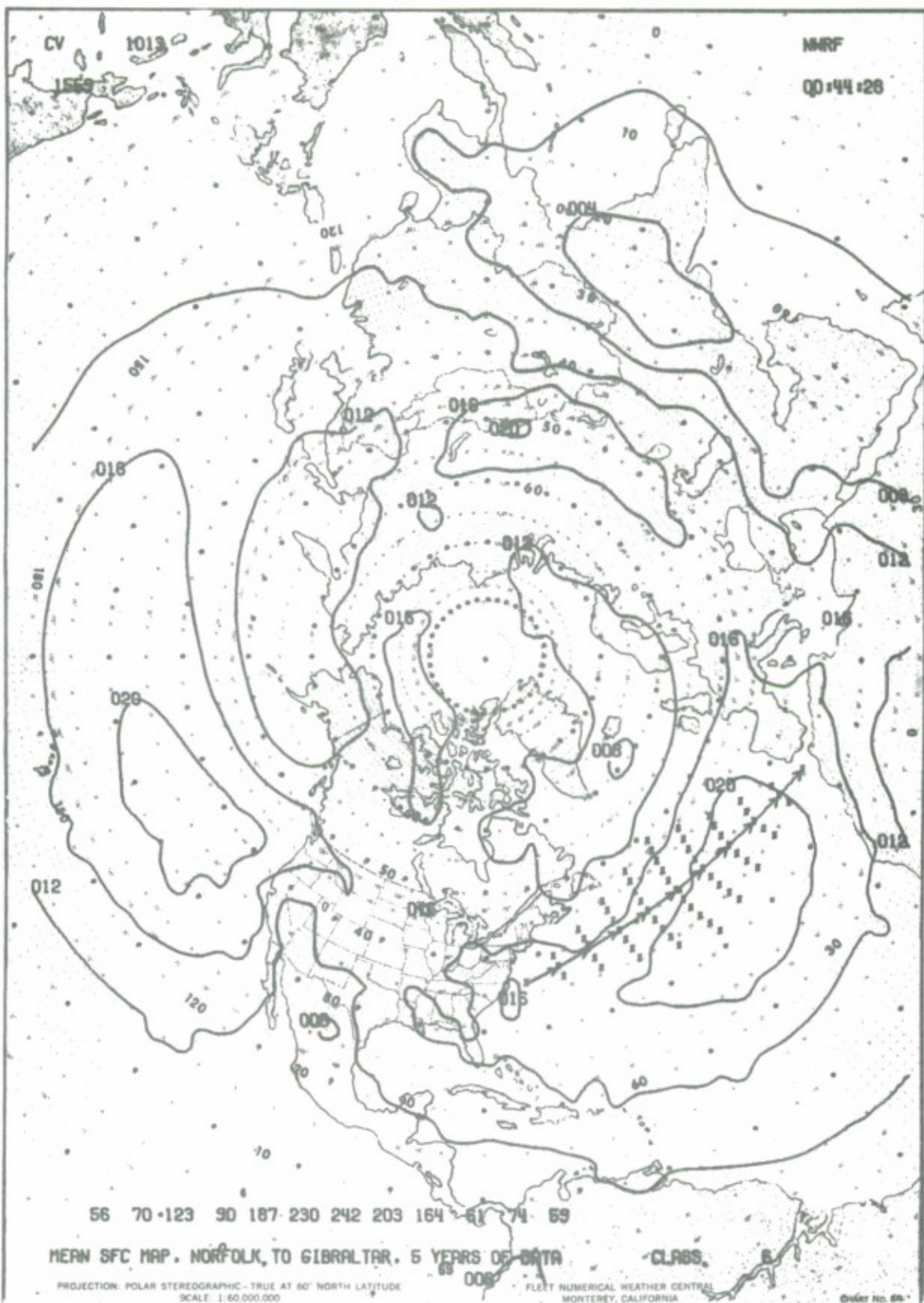
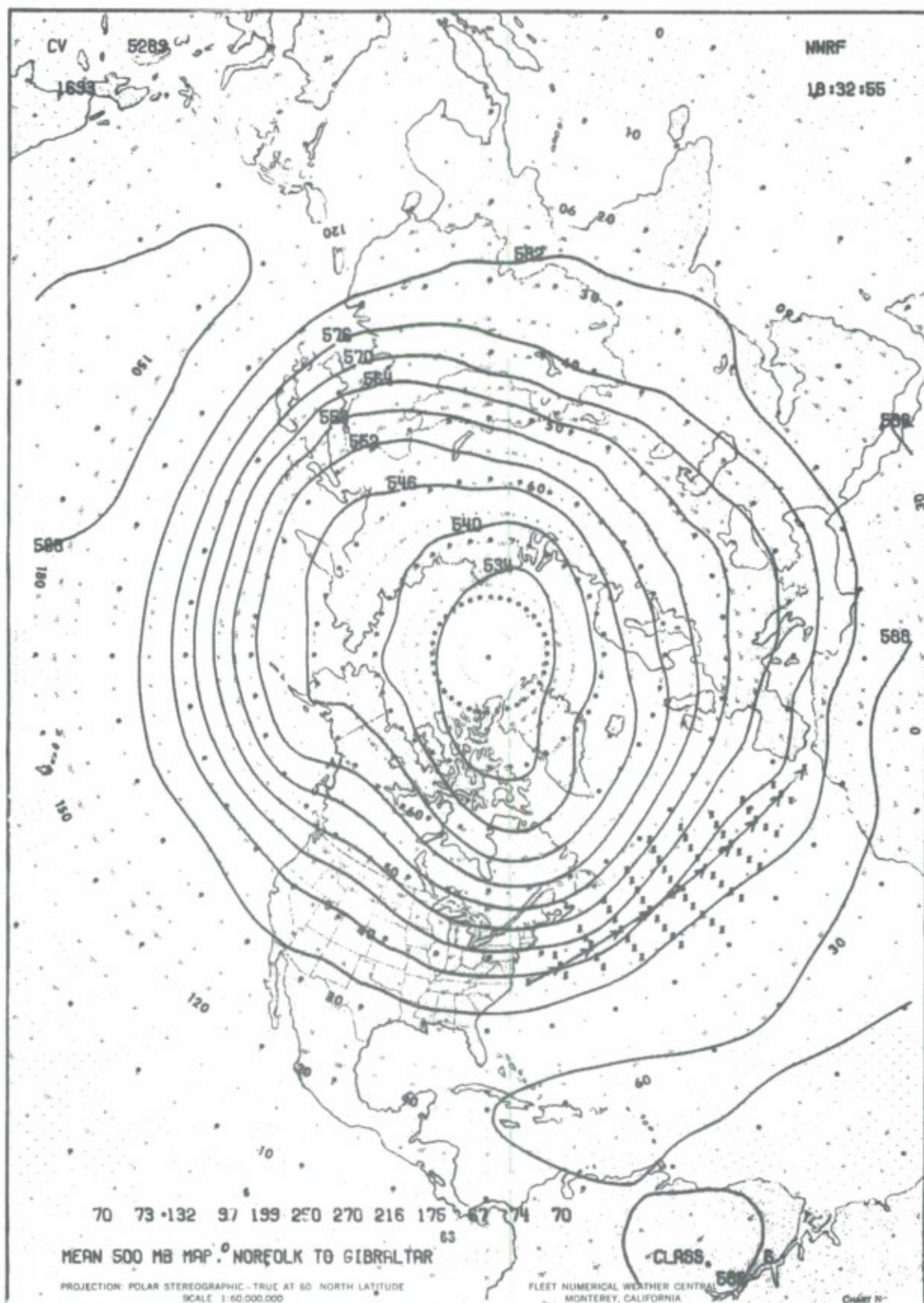


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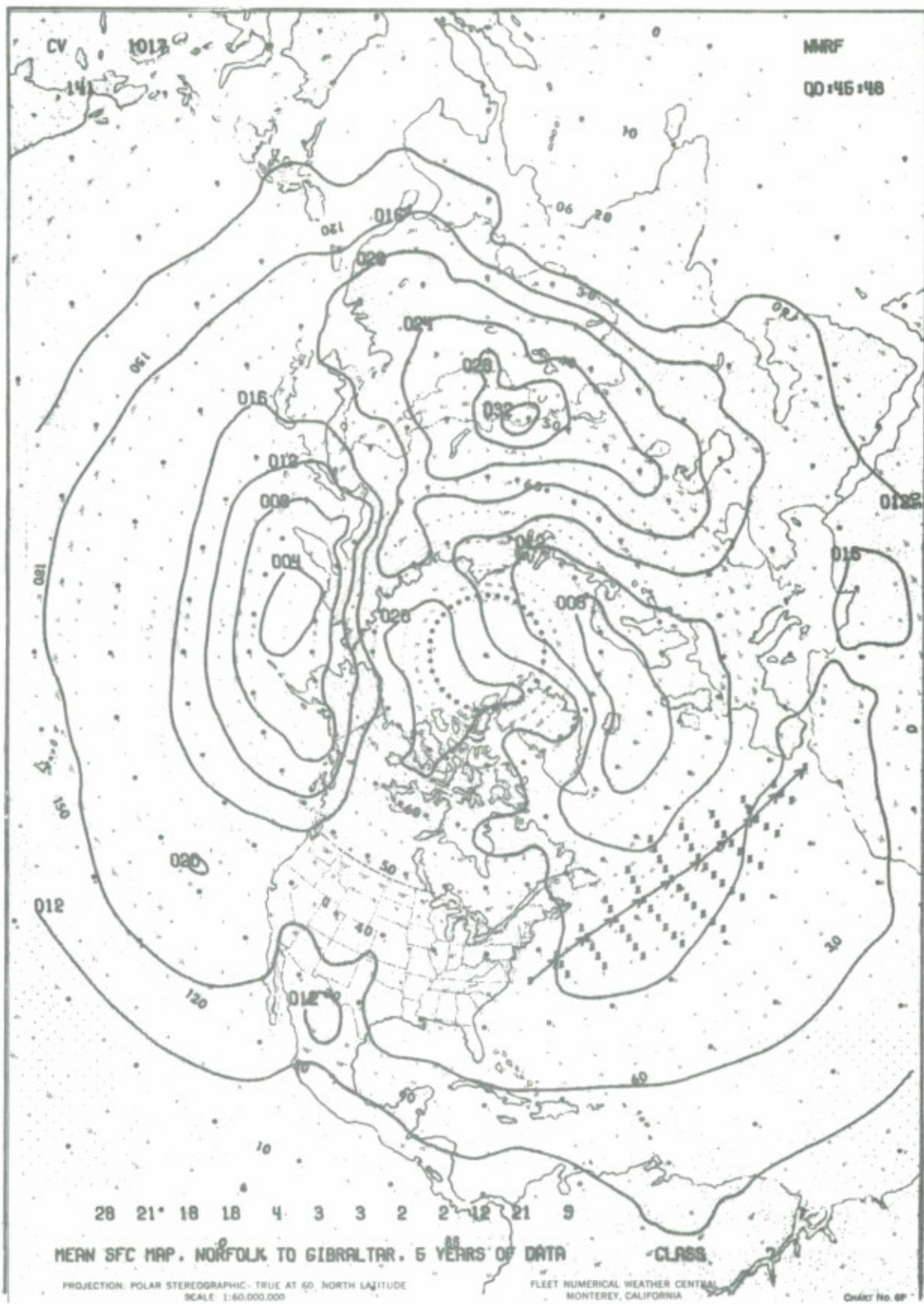


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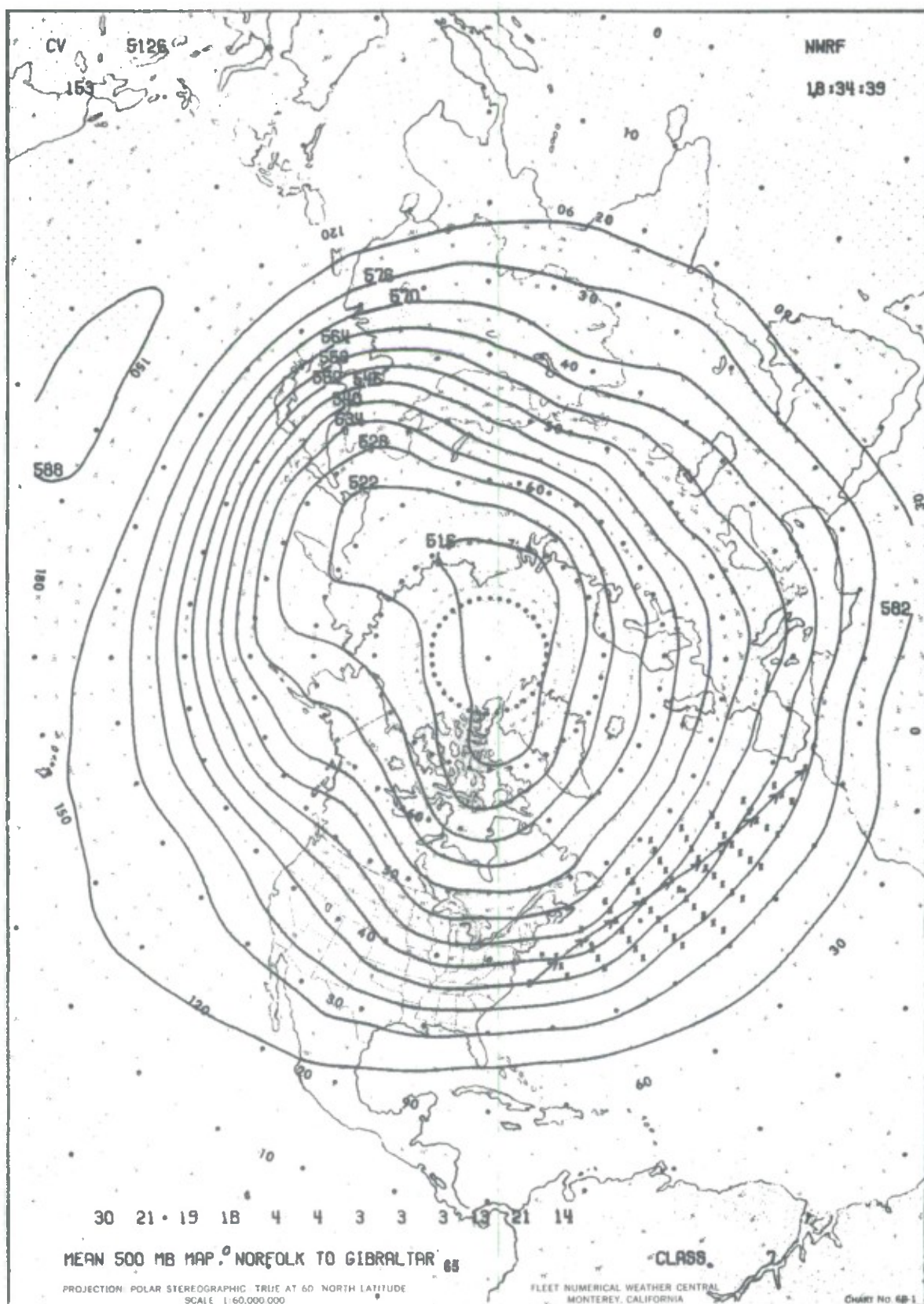


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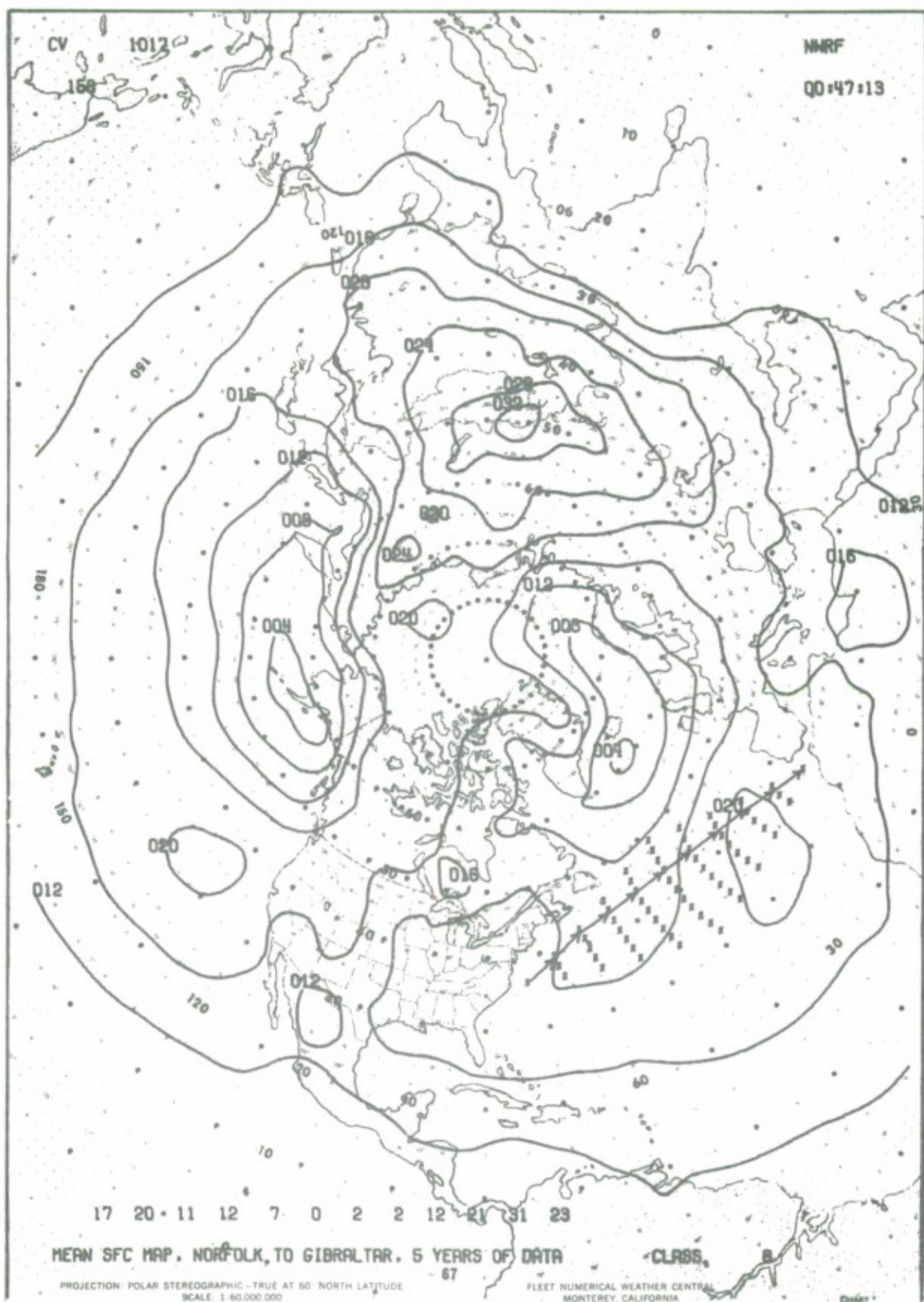


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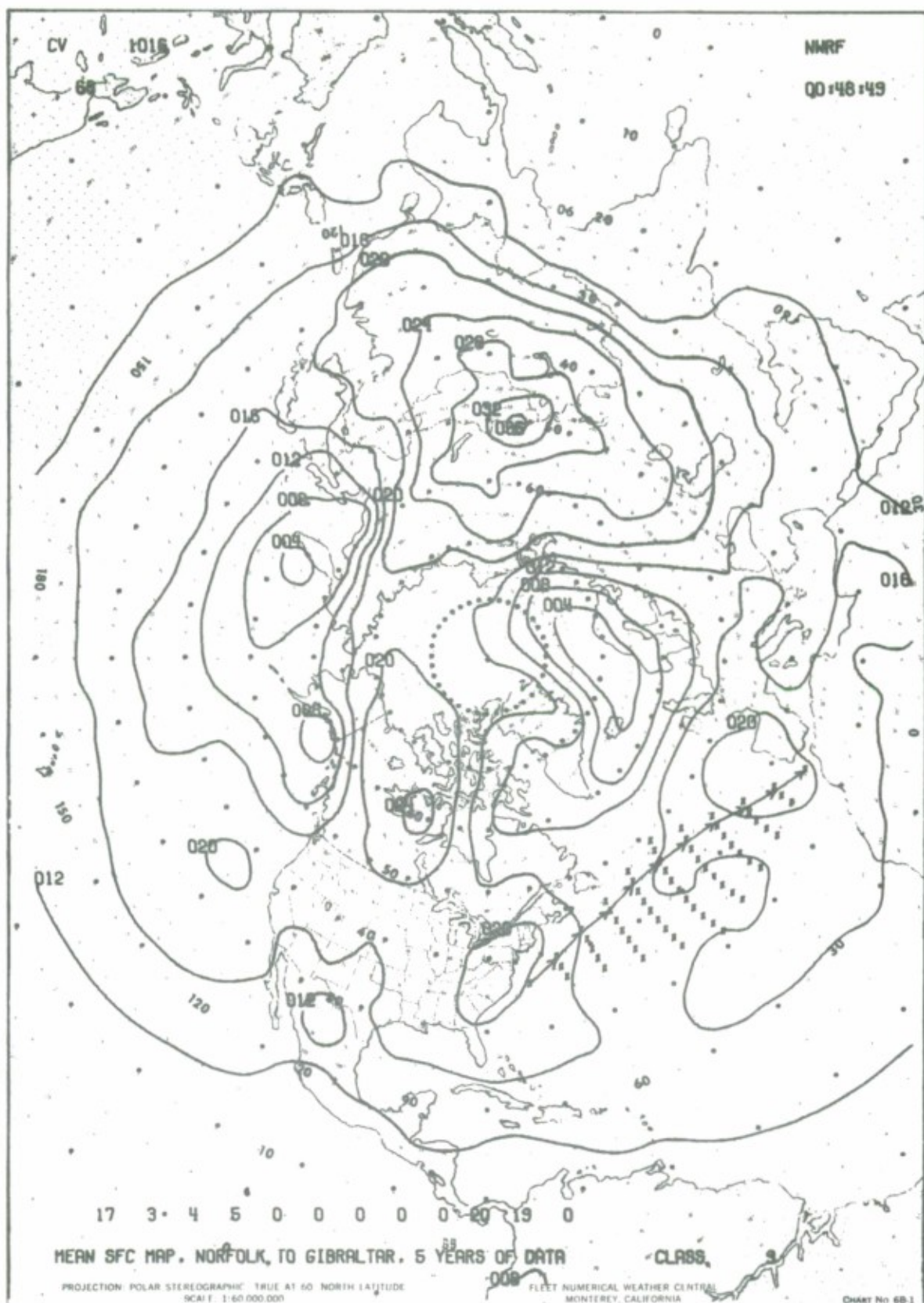


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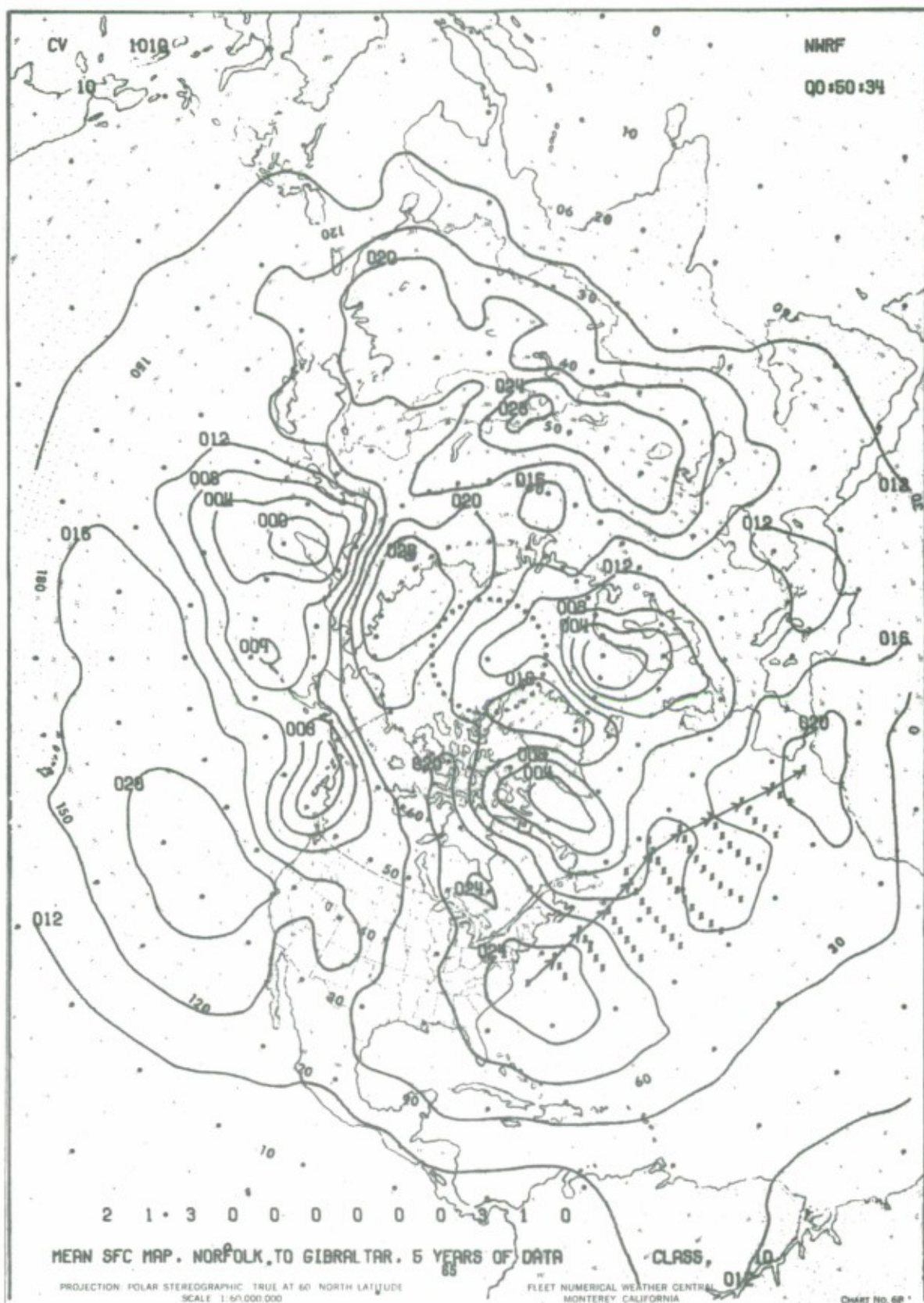


Figure D-10(a).

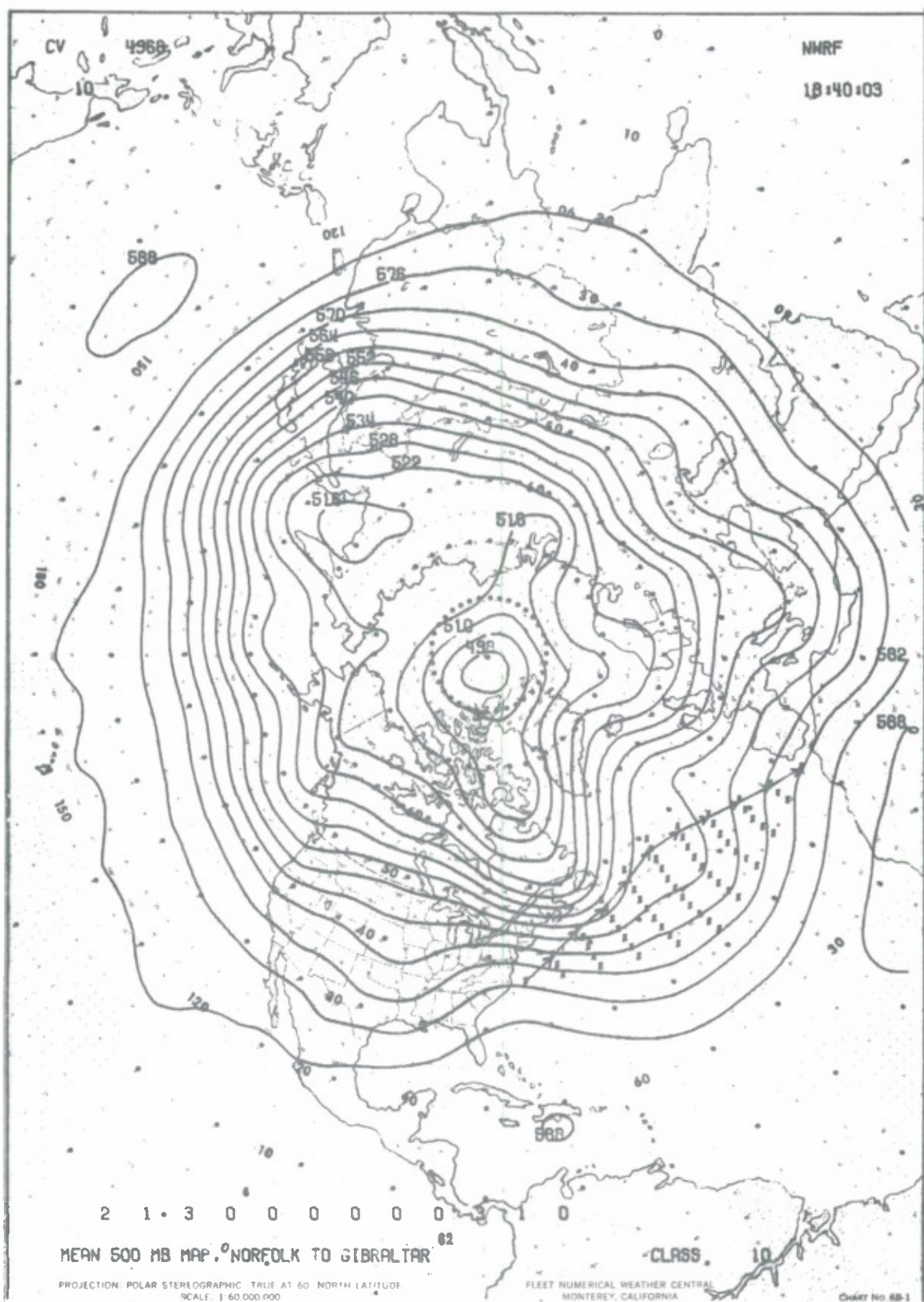


Figure D-10(b).

APPENDIX E

GIBRALTAR TO NORFOLK

20-KNOT VESSEL

FIGURE E-1	Class 2
FIGURE E-2	Class 3
FIGURE E-3	Class 4
FIGURE E-4	Class 5
FIGURE E-5	Class 6
FIGURE E-6	Class 7
FIGURE E-7	Class 8
FIGURE E-8	Class 9
FIGURE E-9	Class 10
FIGURE E-10	Class 11

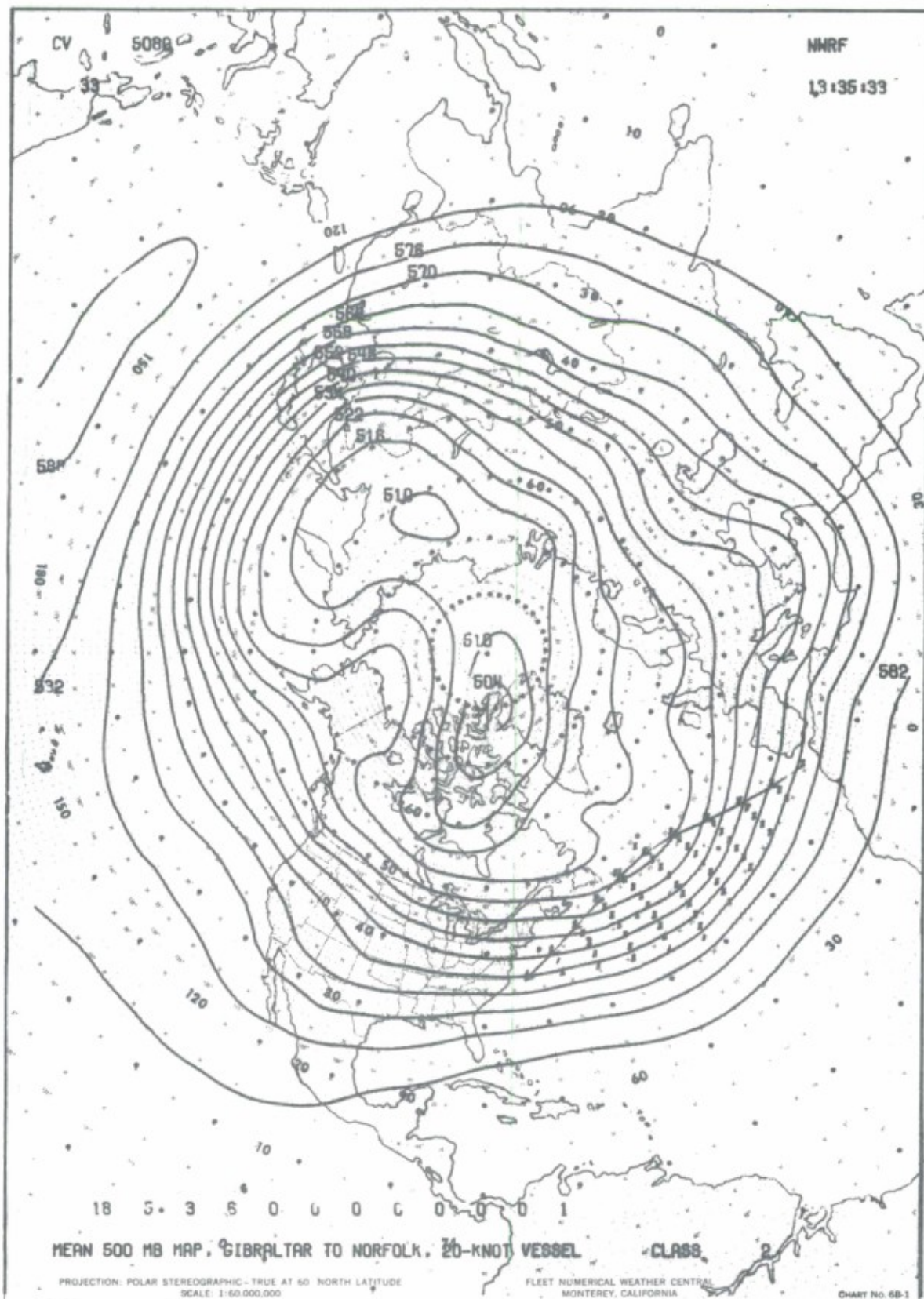


Figure E-1(b).

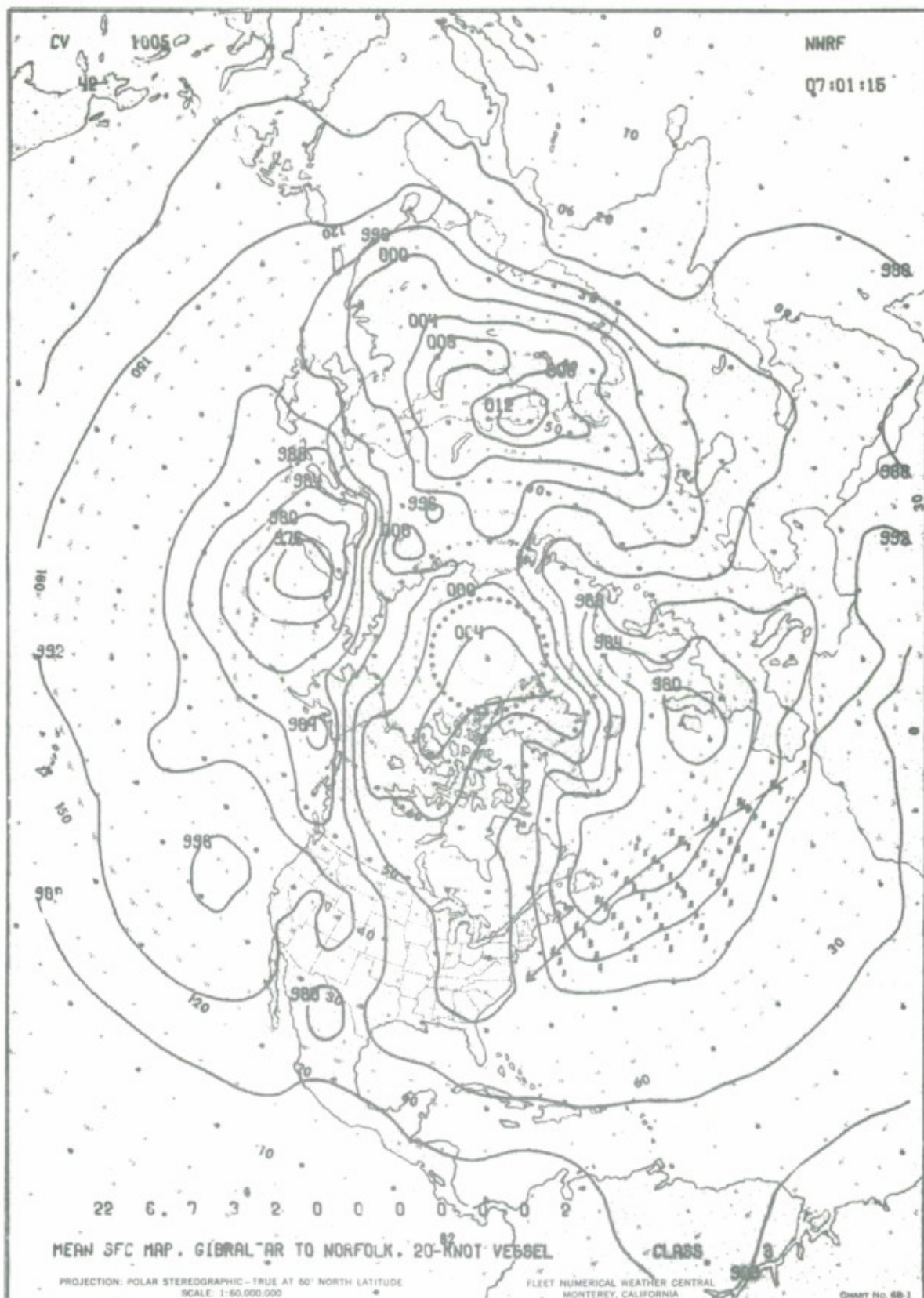


Figure E-2(a).

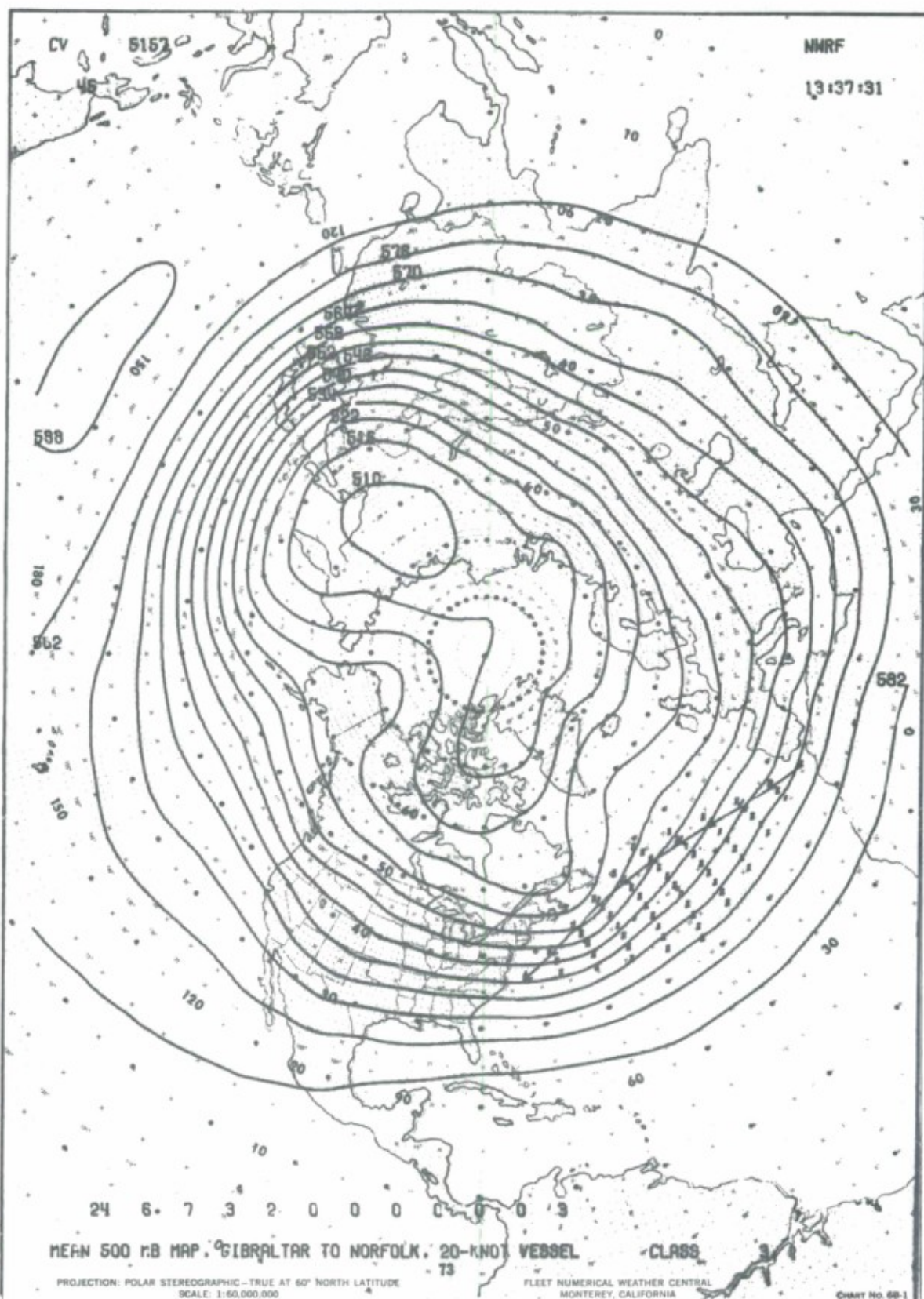


Figure E-2(b).

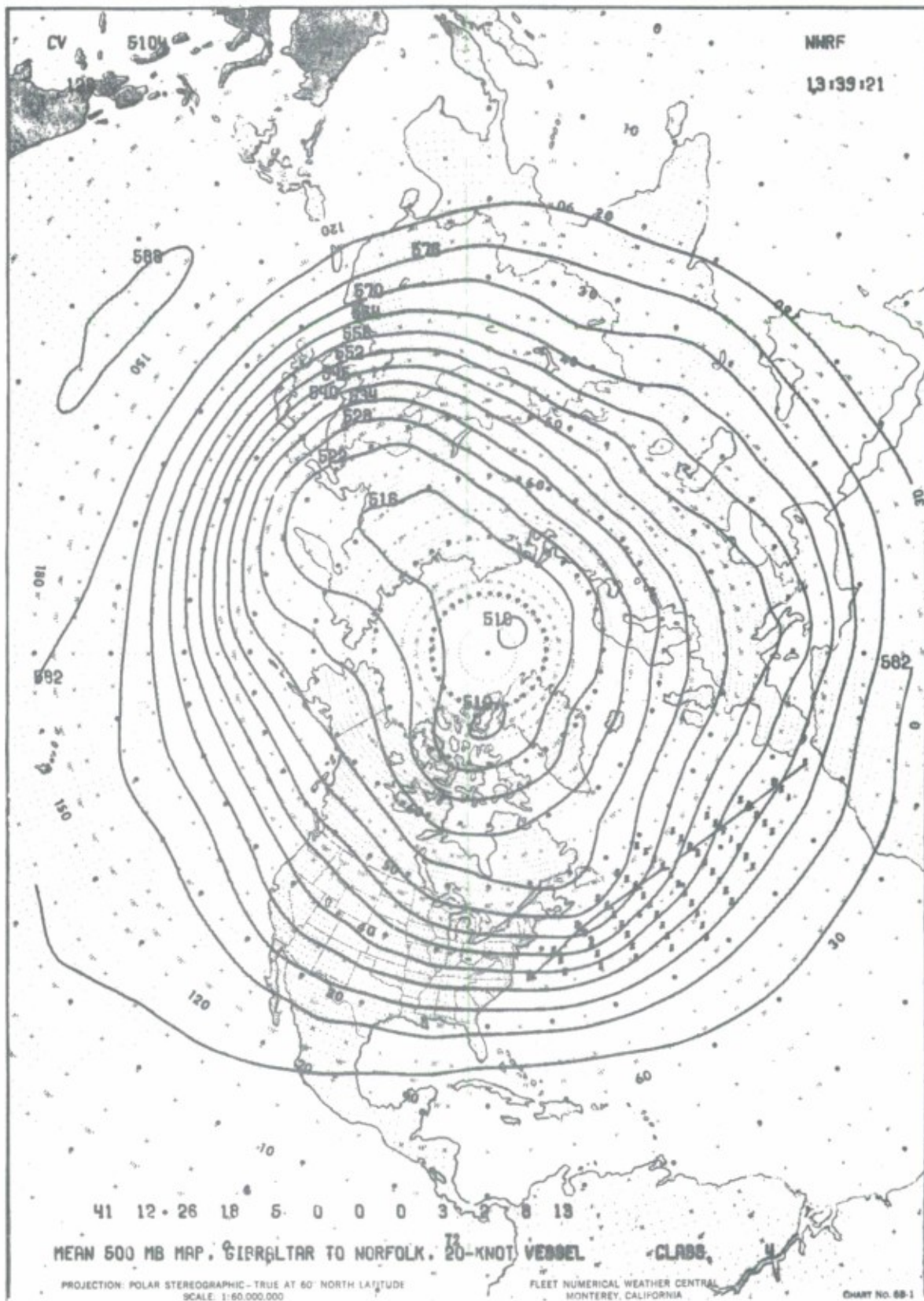


Figure E-3(b).

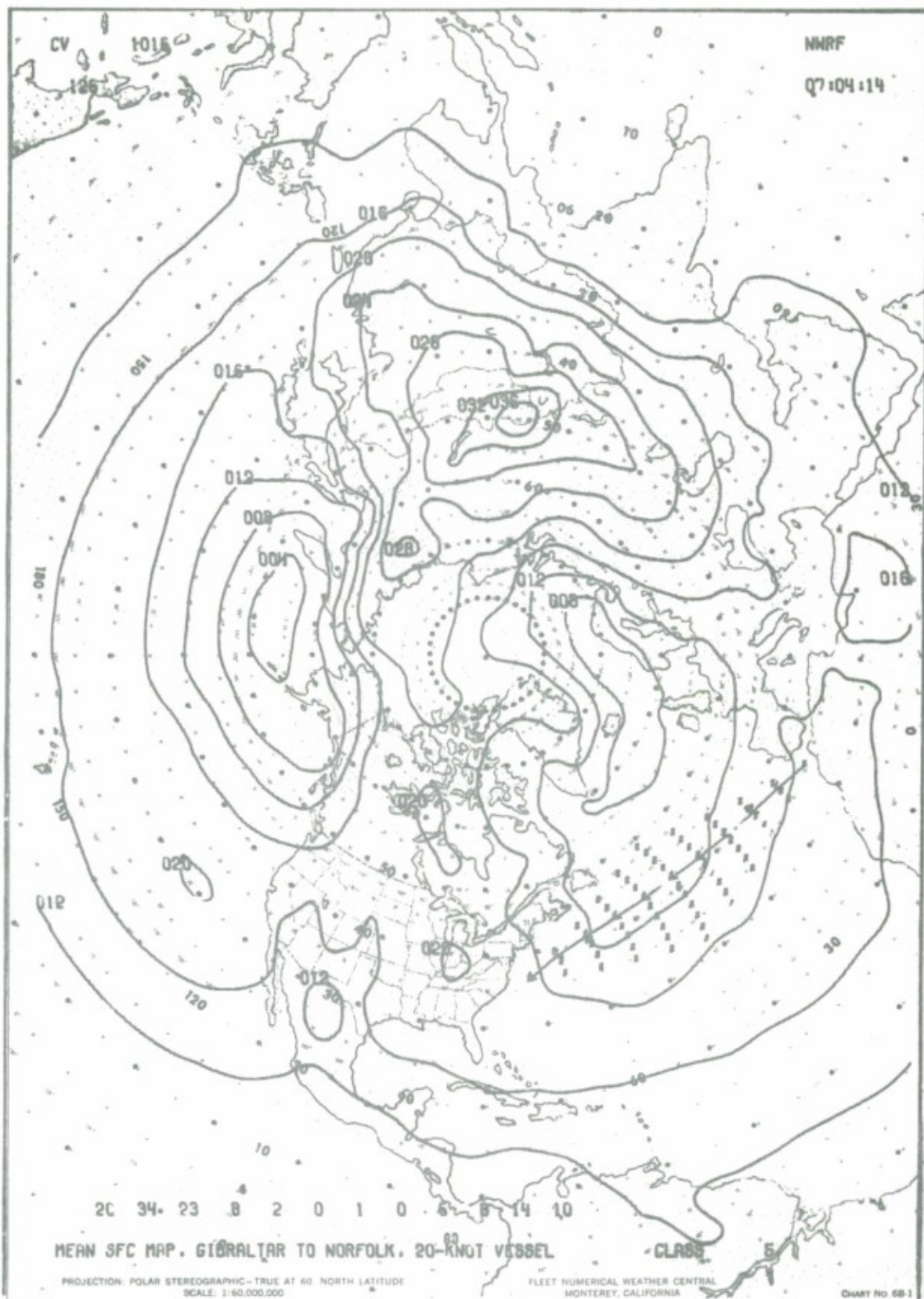


Figure E-4(a).

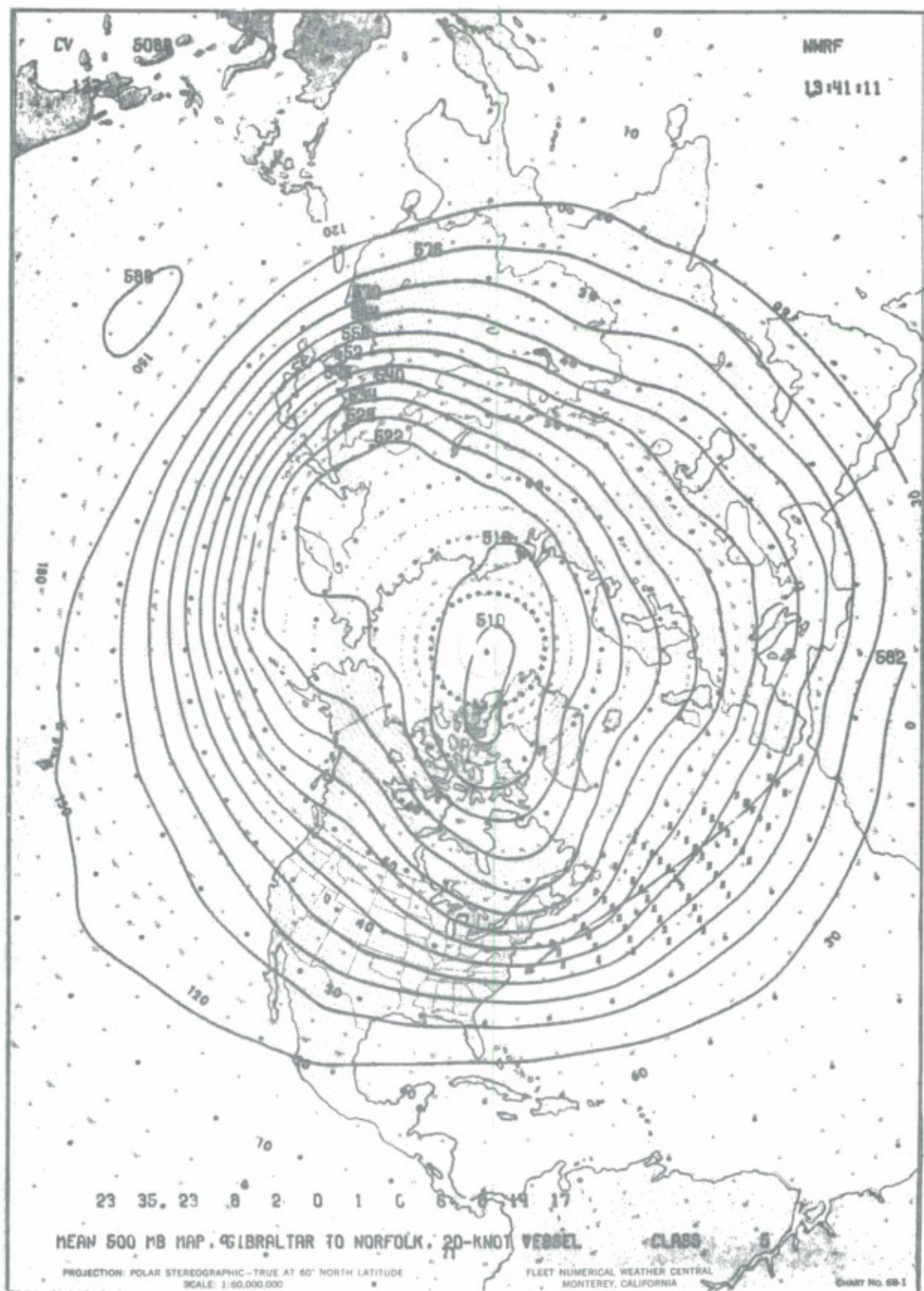


Figure E-4(b).

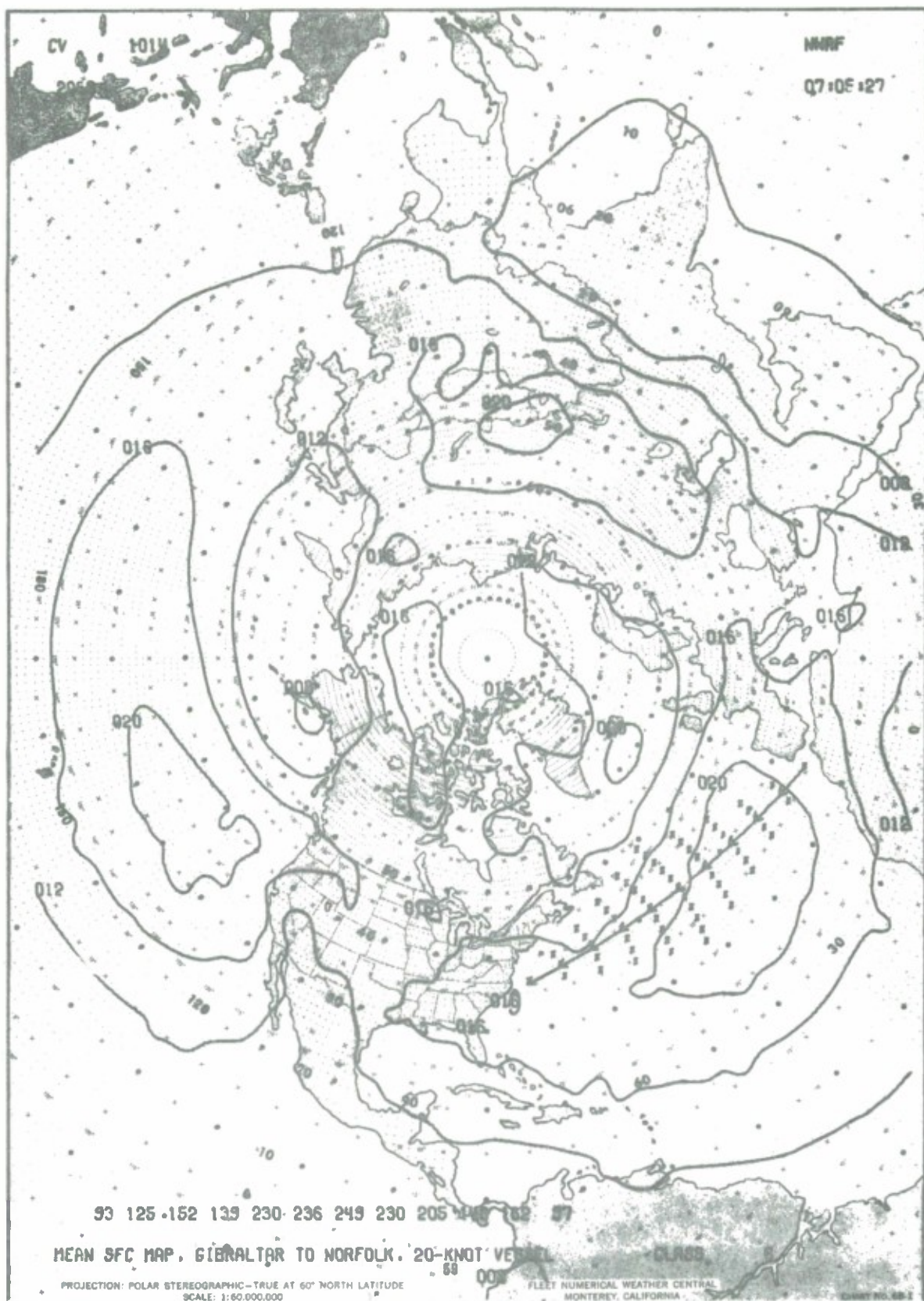


Figure E-5(a).

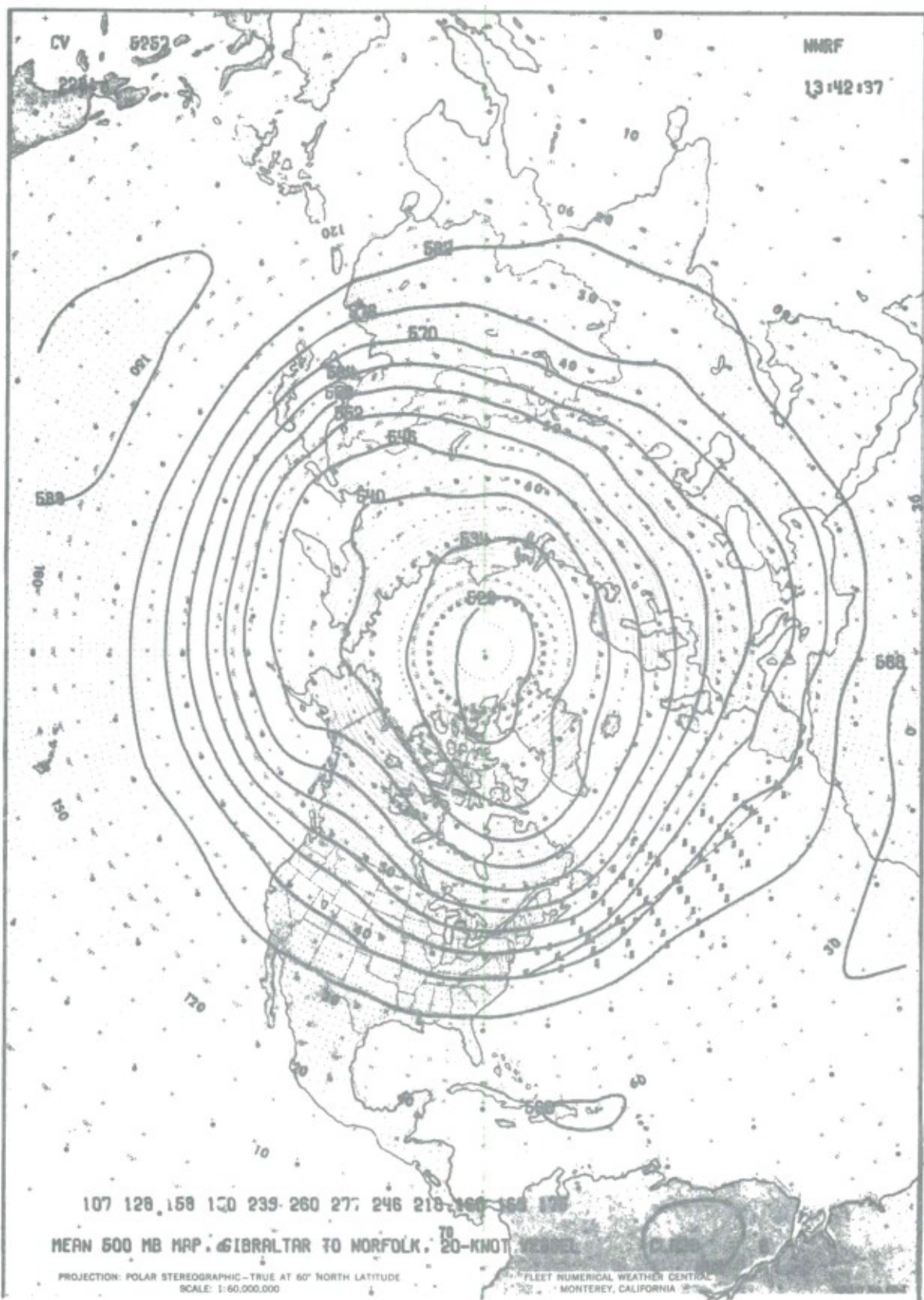


Figure E-5(b).

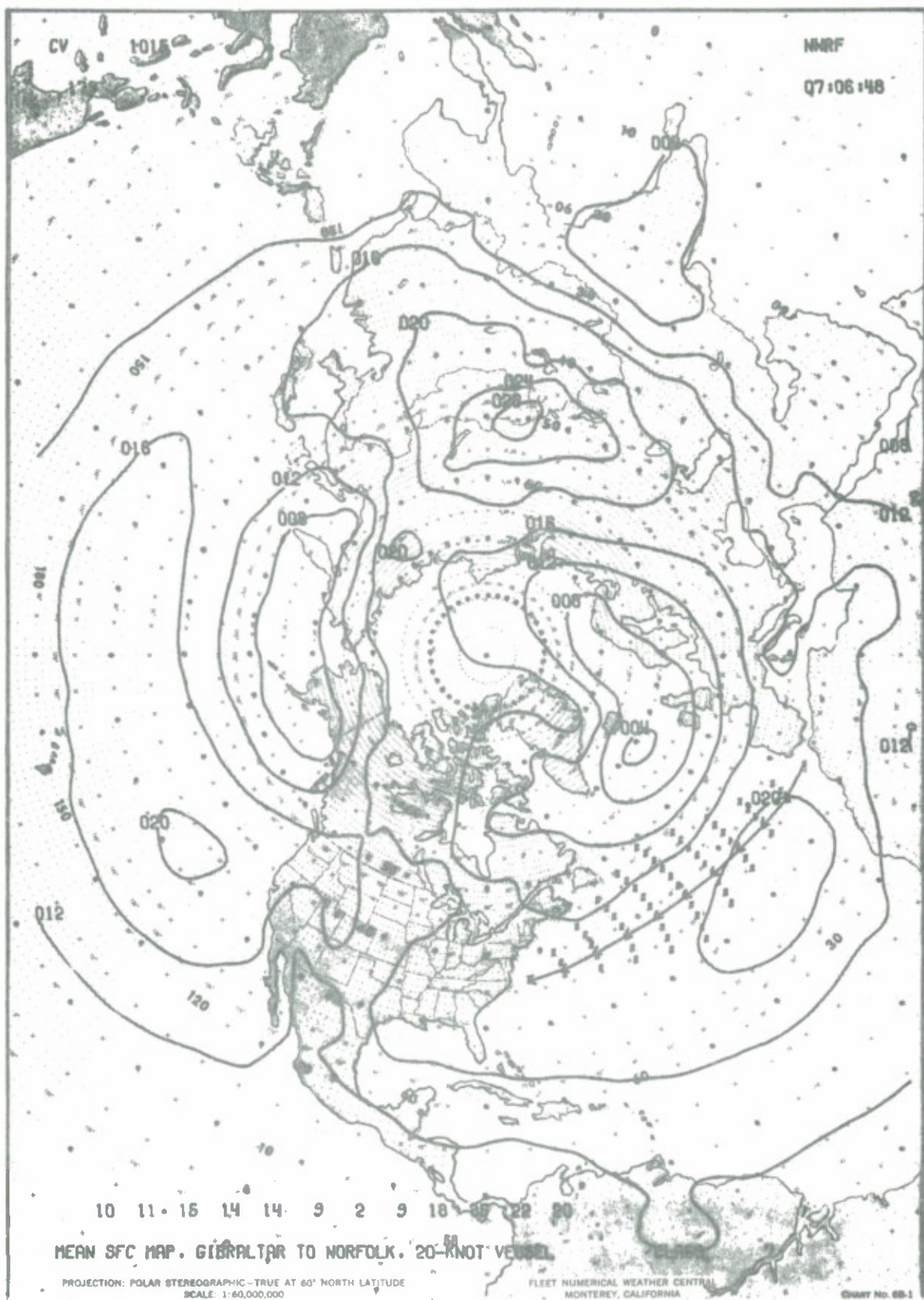


Figure E-6(a).

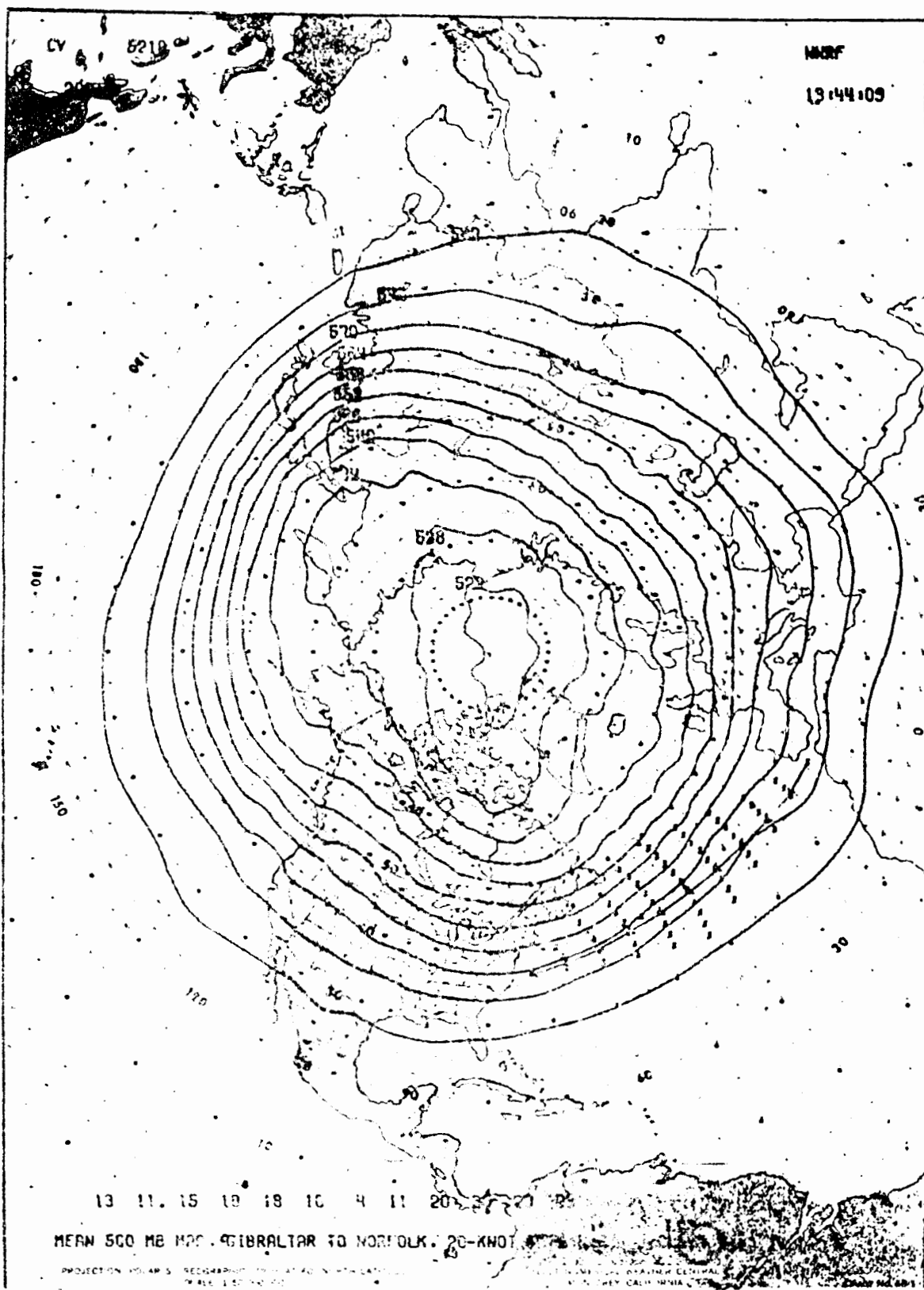


Figure E-6(b).

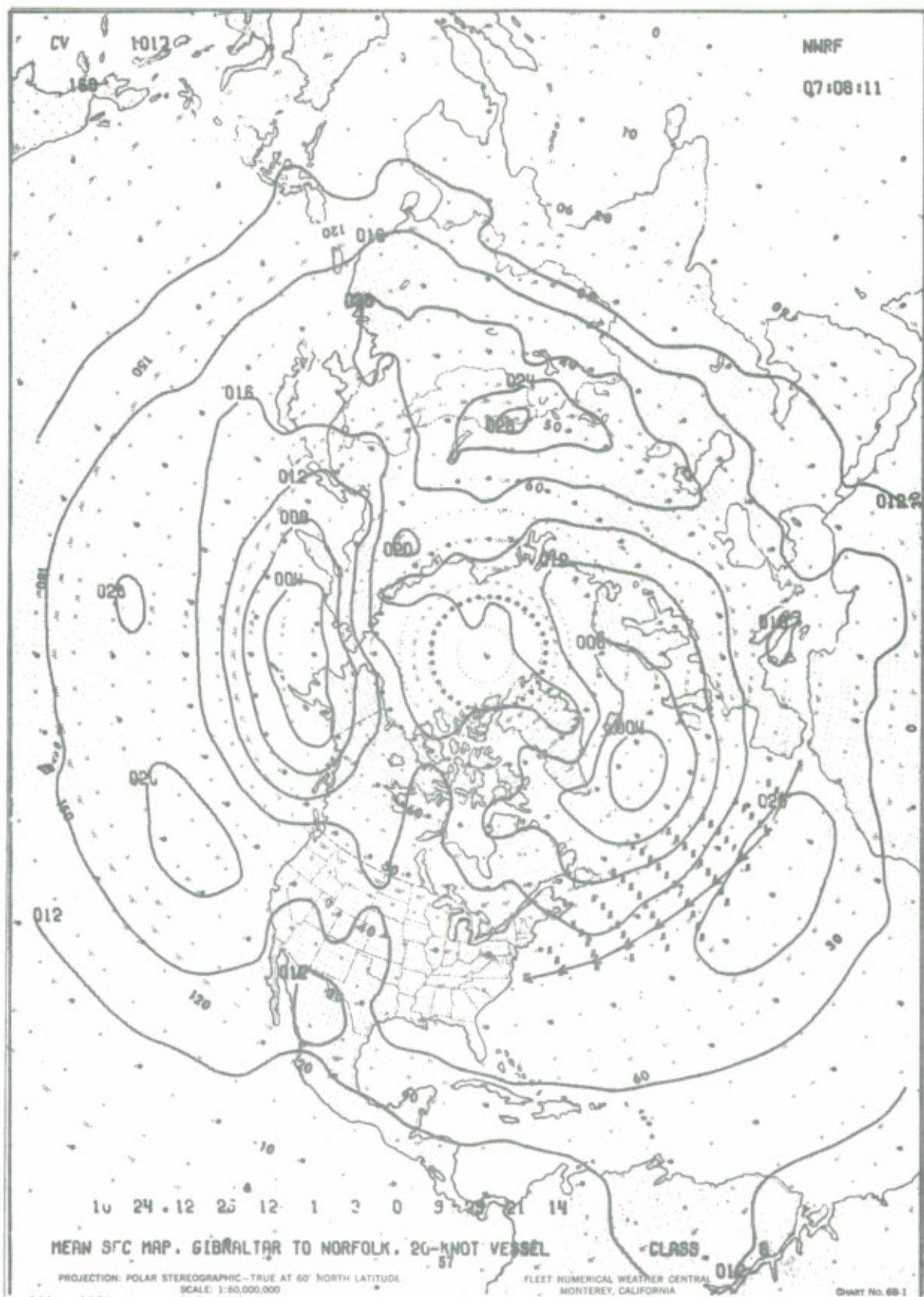


Figure E-7(a).

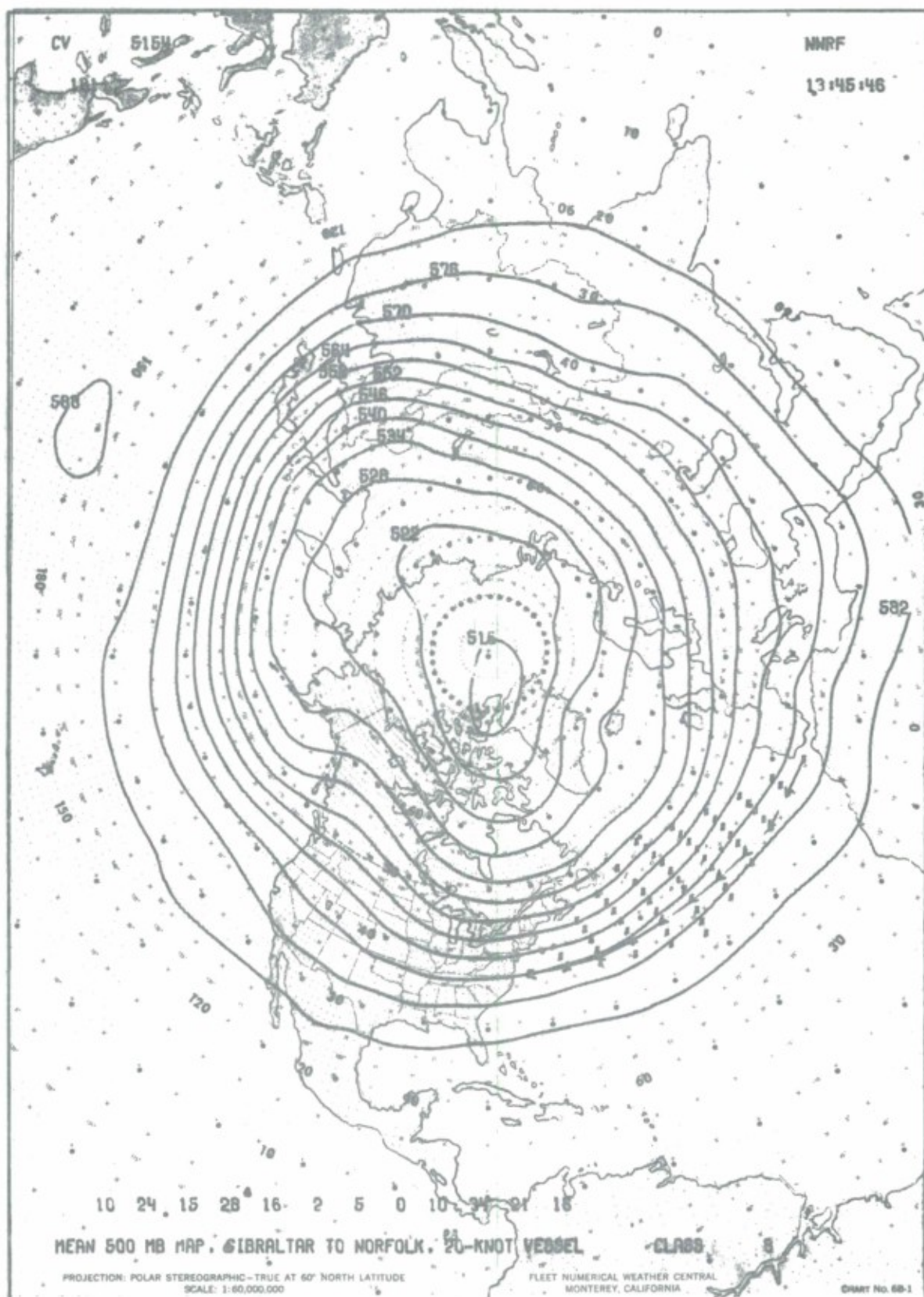


Figure E-7(b).

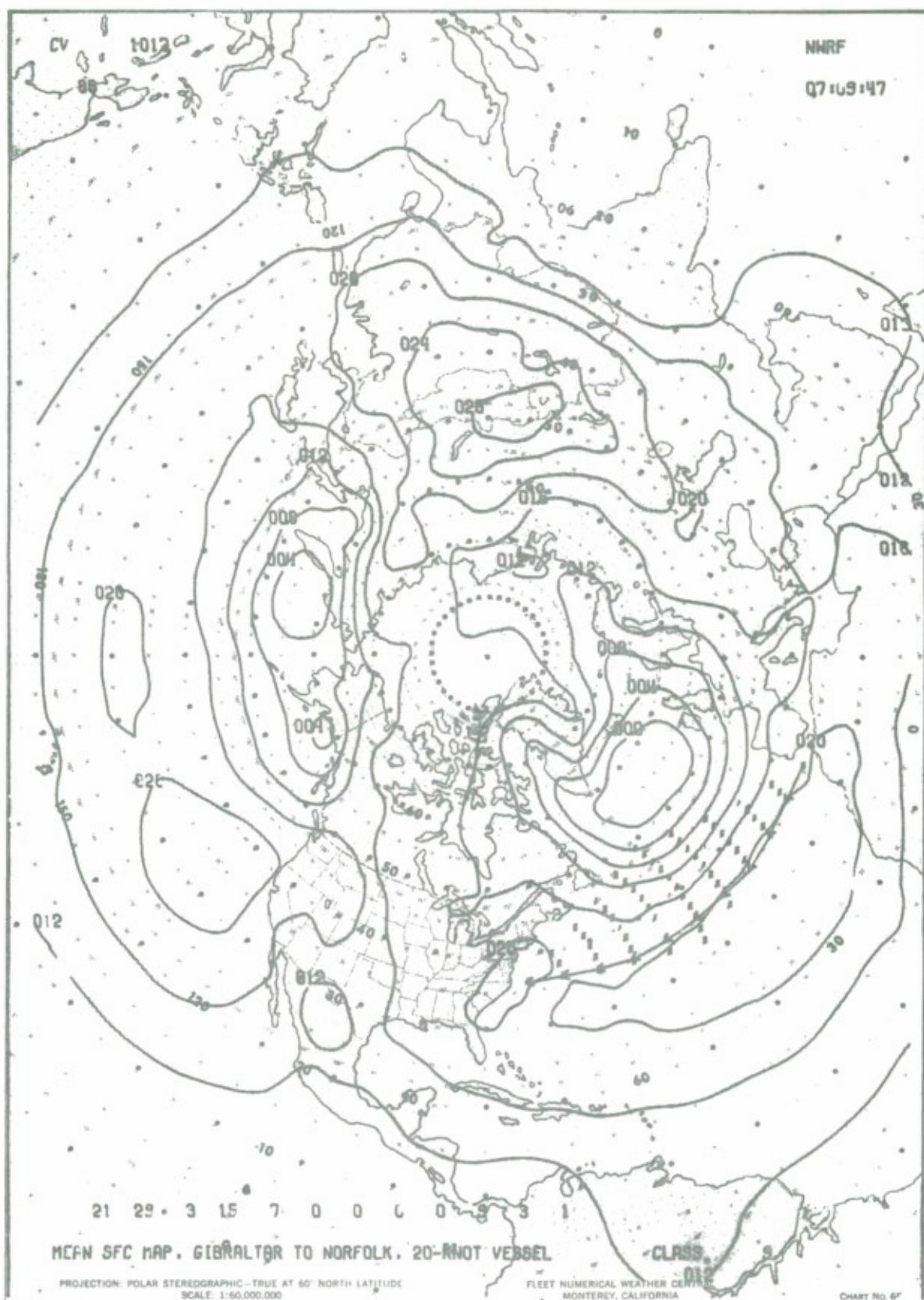


Figure E-8(a).

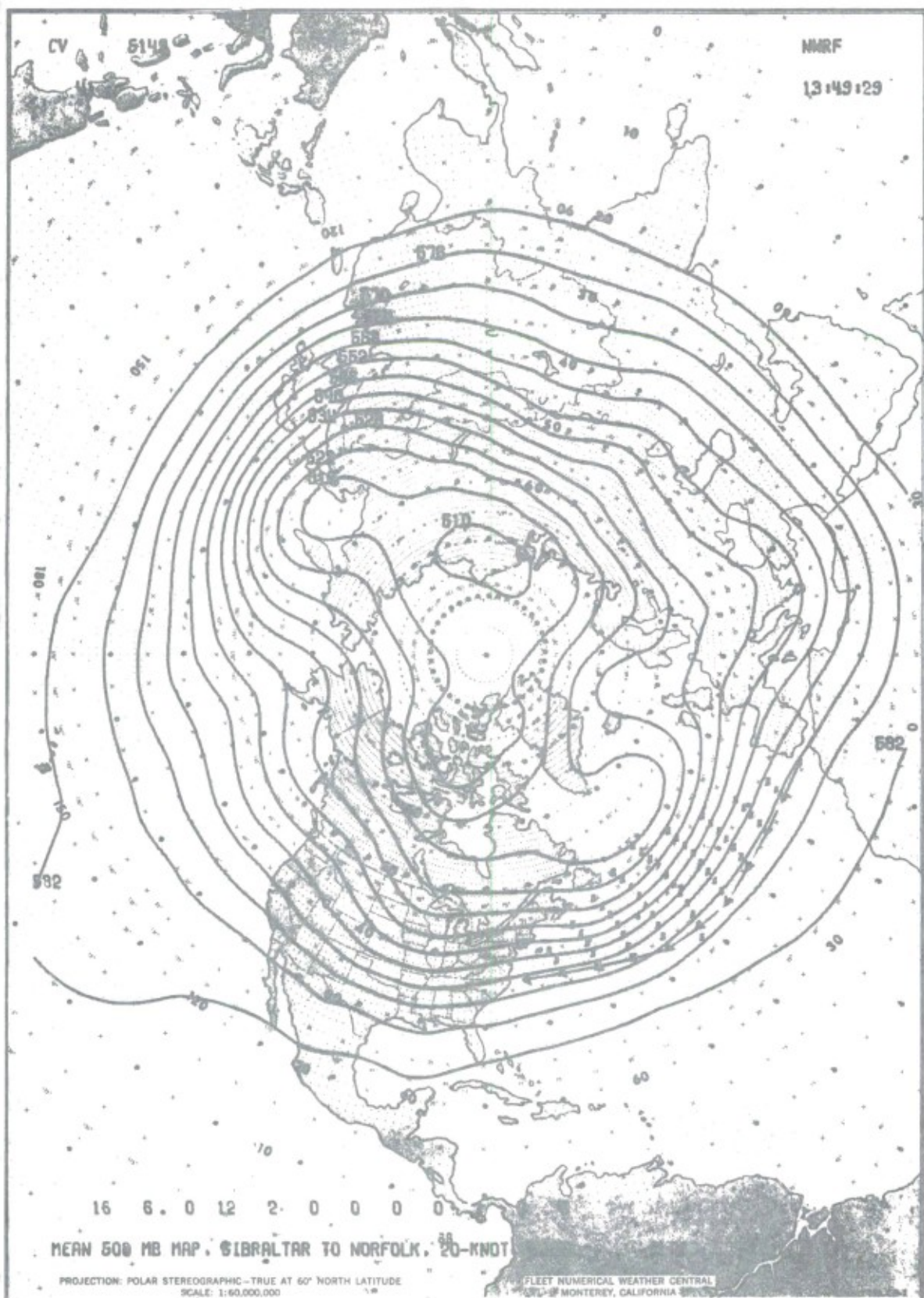
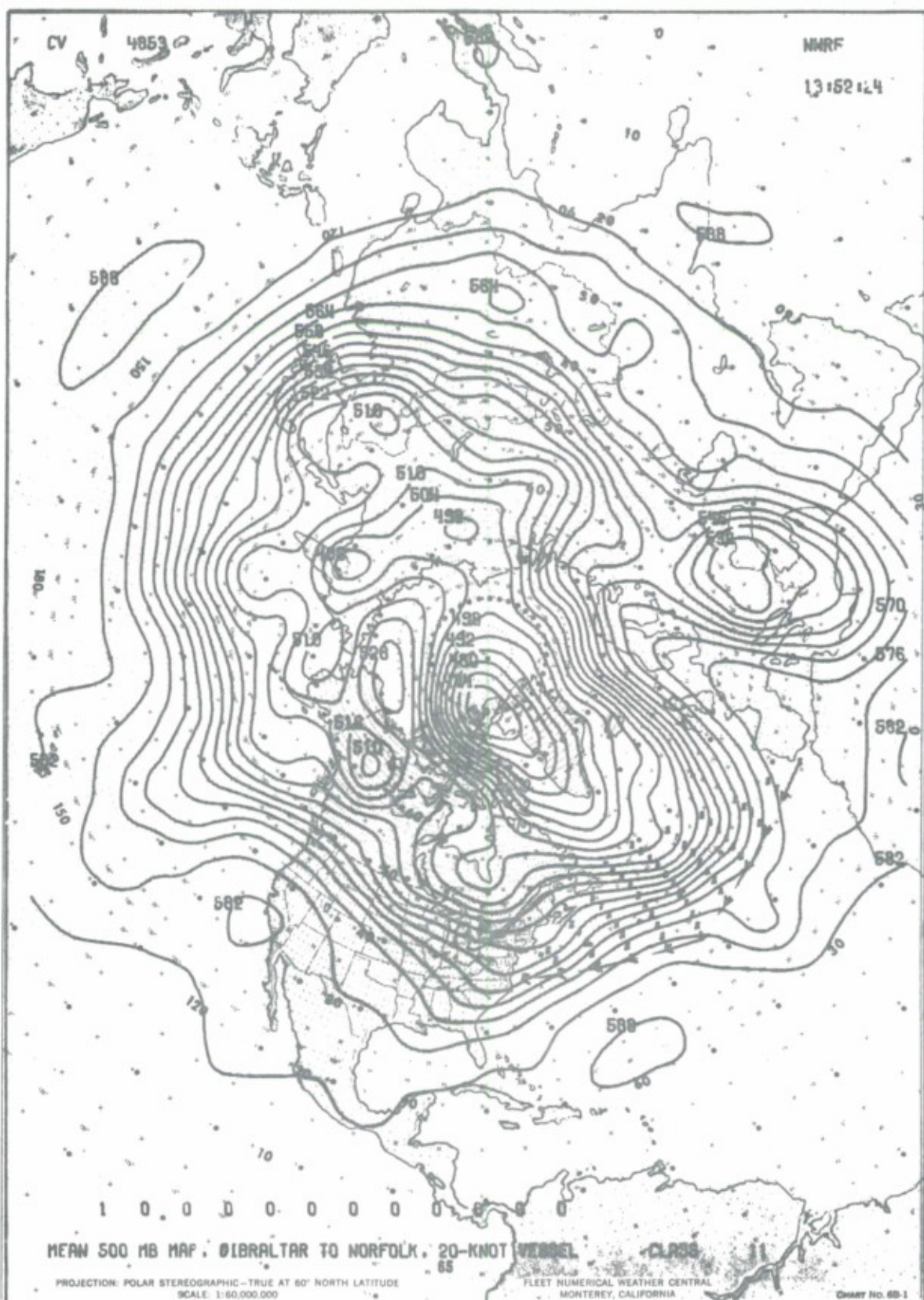


Figure E-9(b).



APPENDIX F

NORFOLK TO BISHOP ROCK

20-KNOT VESSEL

FIGURE F-1	Class 2
FIGURE F-2	Class 3
FIGURE F-3	Class 4
FIGURE F-4	Class 5
FIGURE F-5	Class 6
FIGURE F-6	Class 7

MEAN SFC MAP, NORFOLK TO BISHOP ROCK

20-KNOT VESSEL

CLASS 2

MISSING

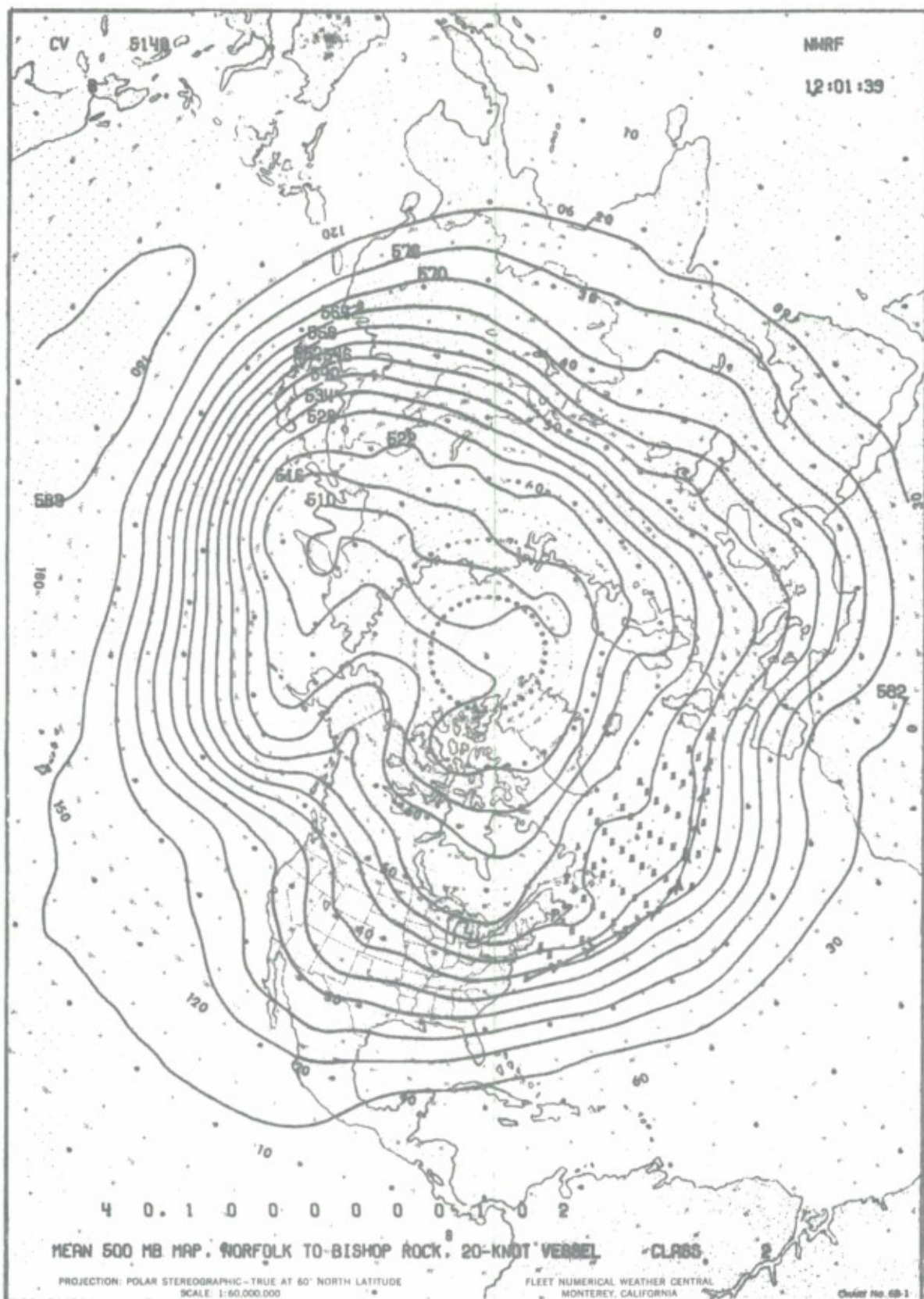


Figure F-1(b).

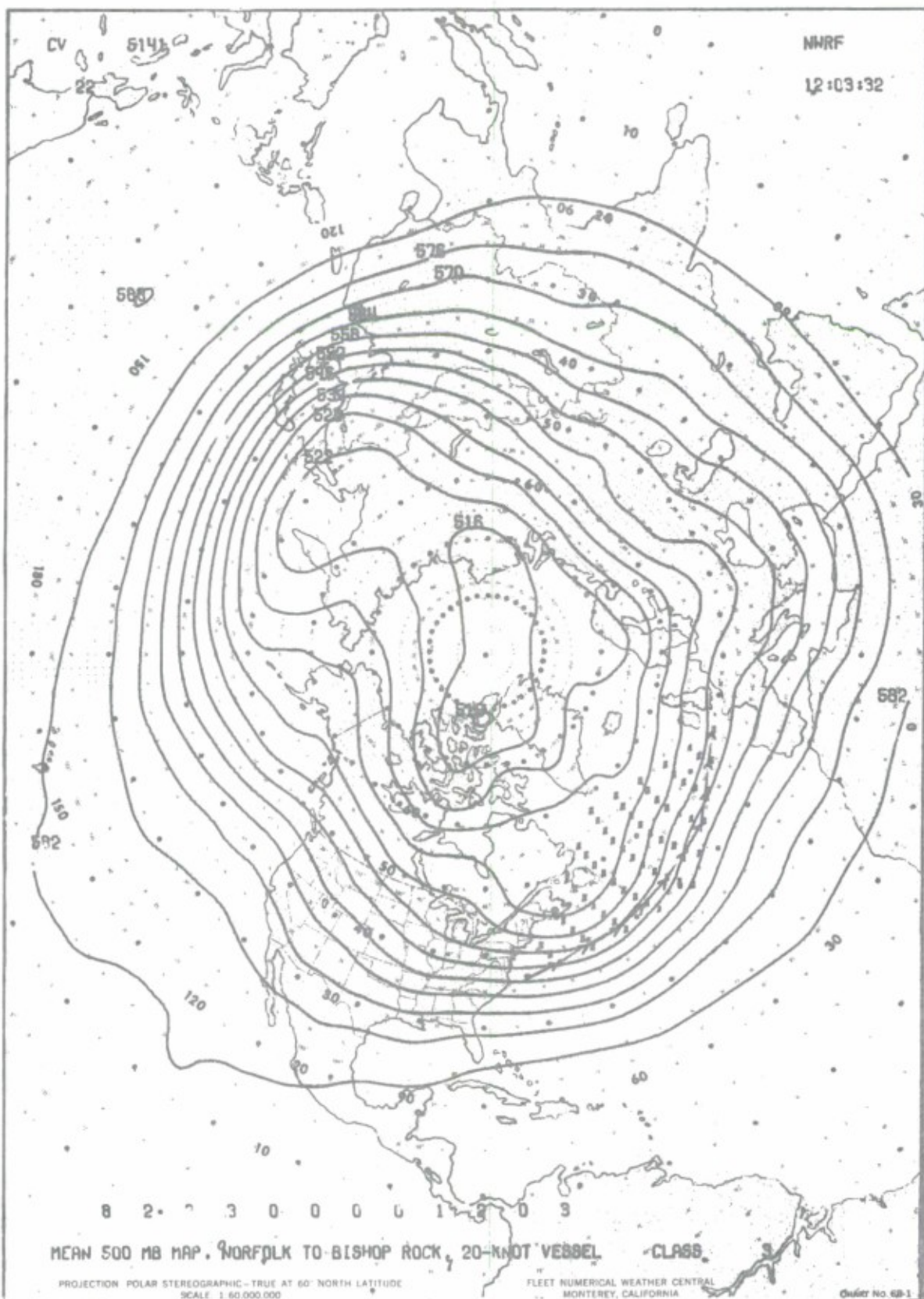


Figure F-2(b).

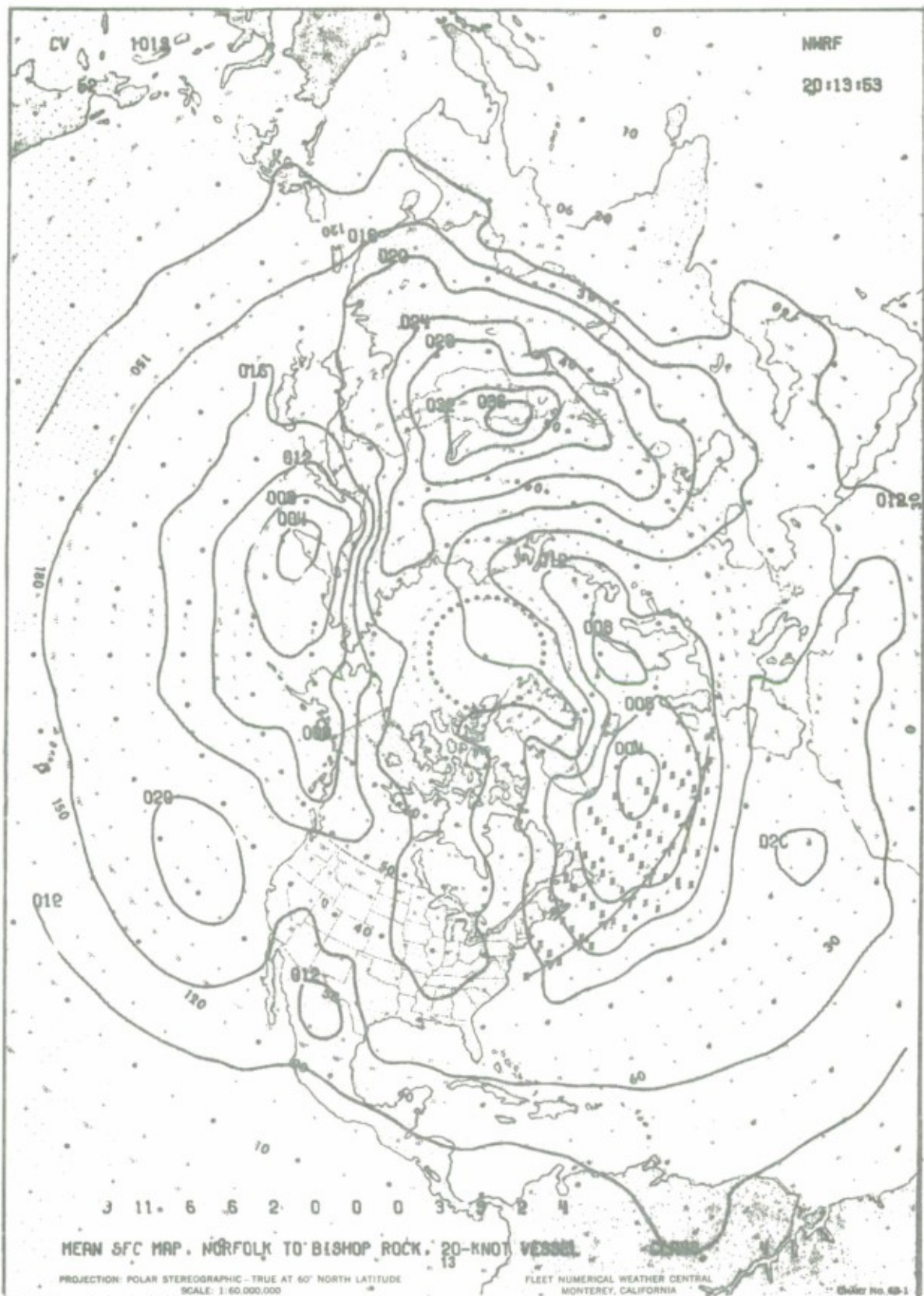


Figure F-3(a).

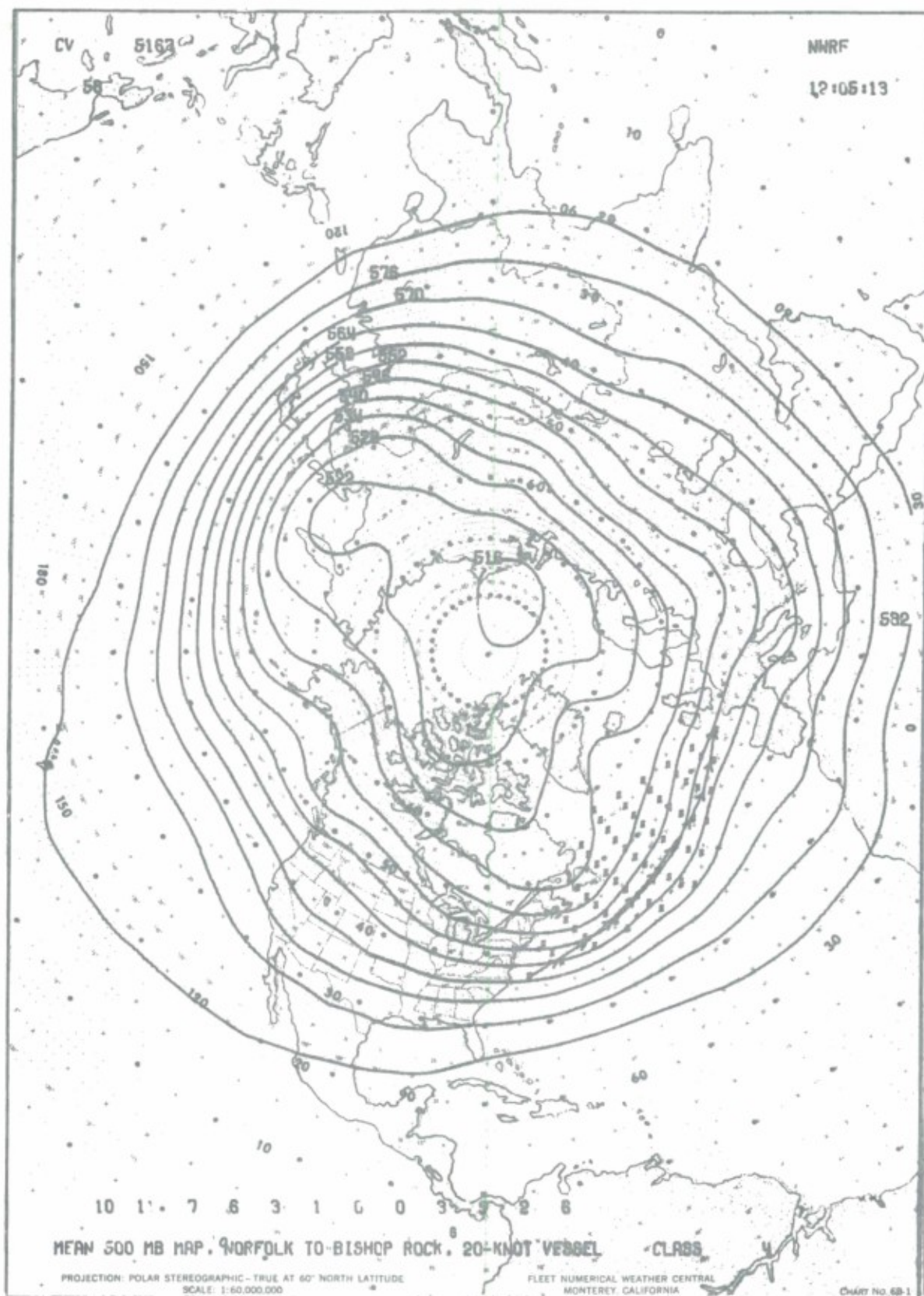


Figure F-3(b).

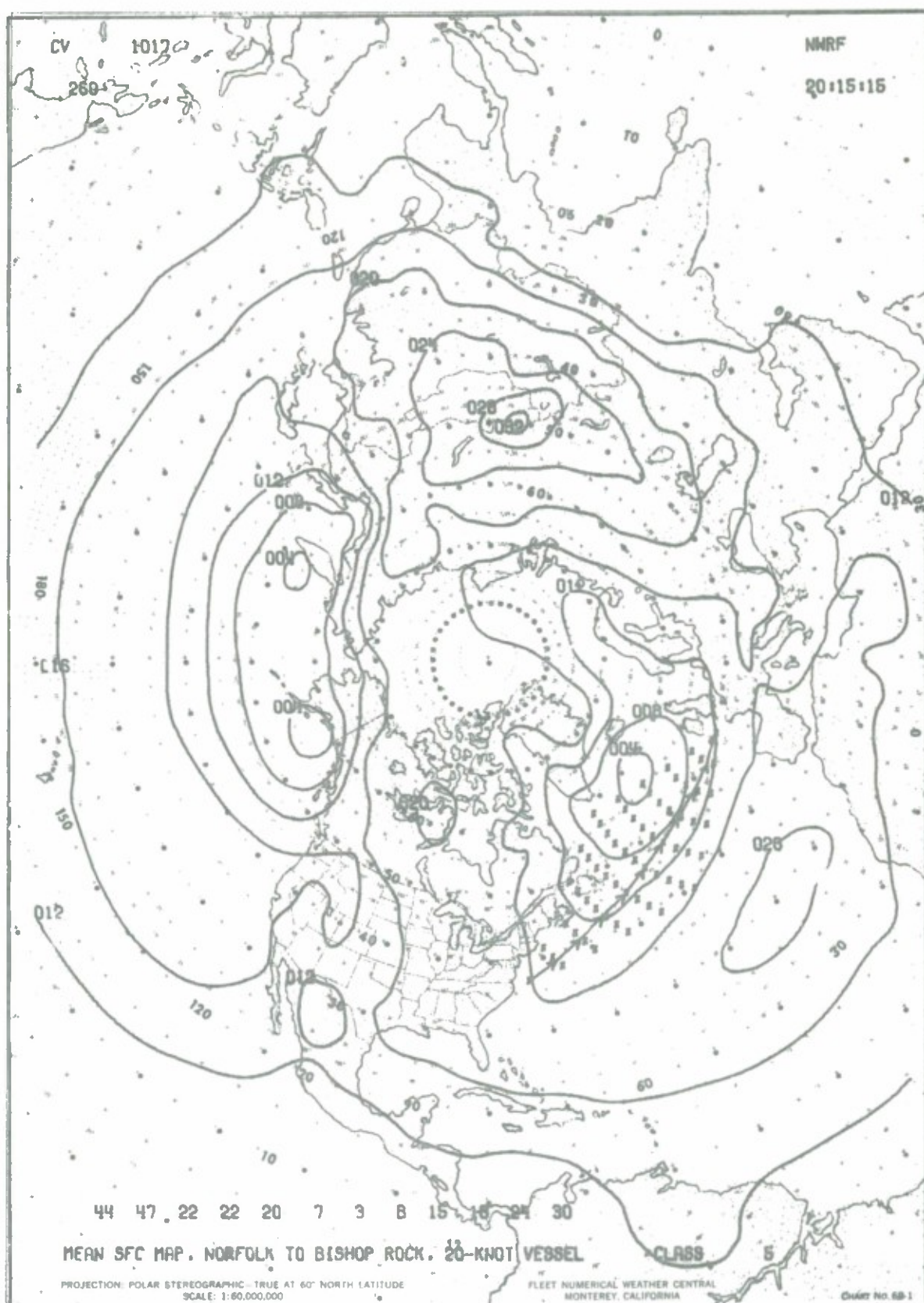


Figure F-4(a).

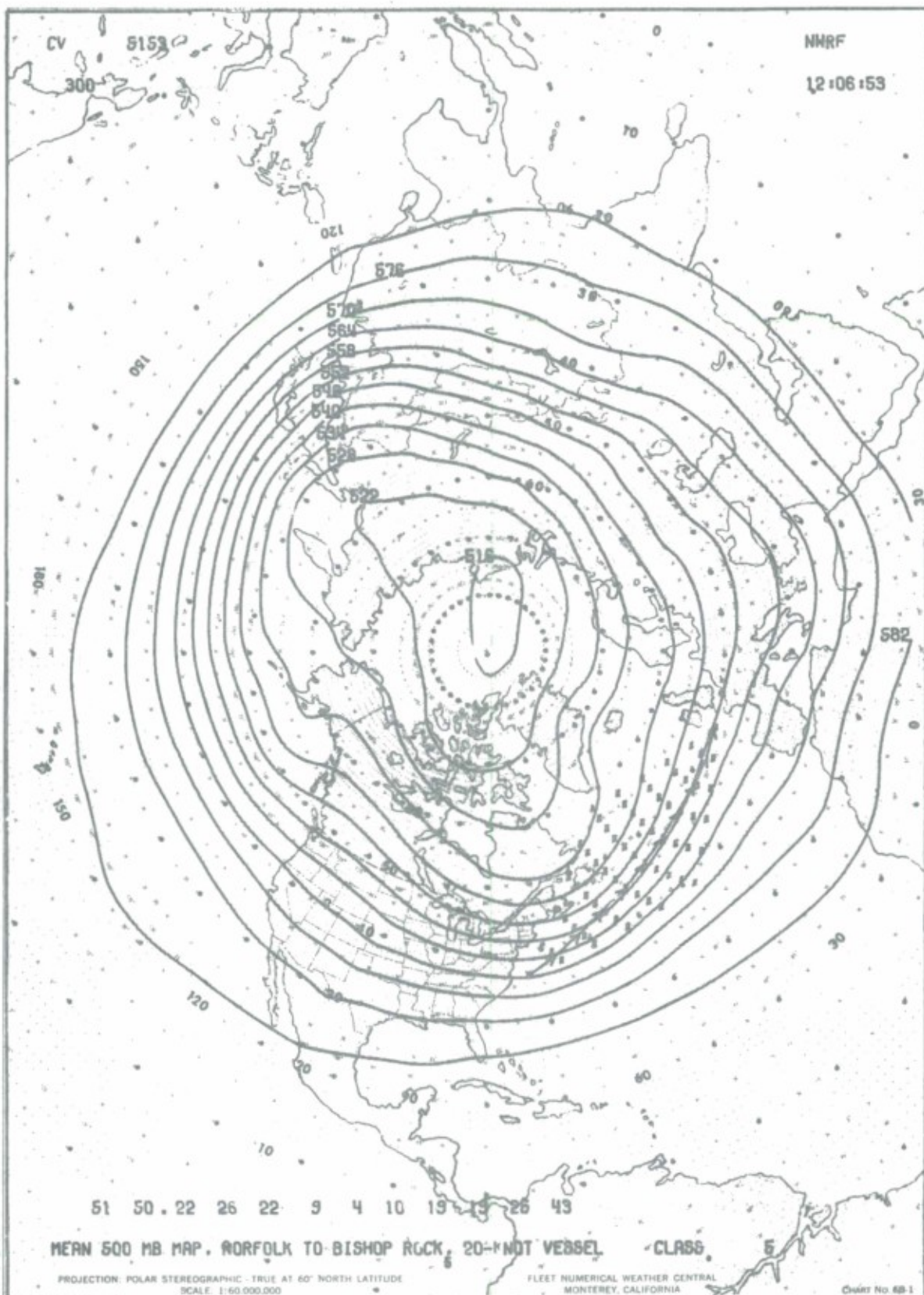


Figure F-4(b).

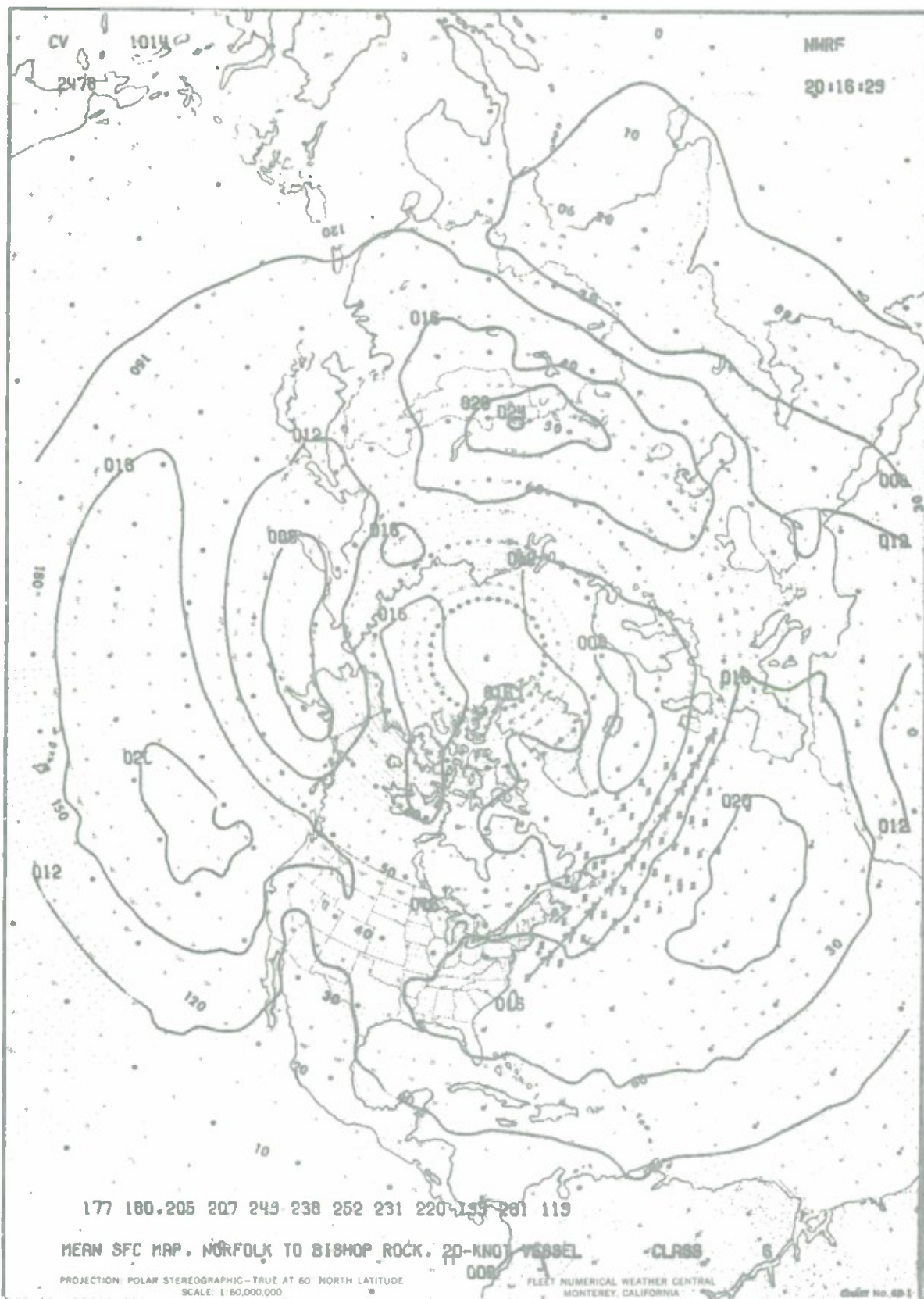


Figure F-5(a).

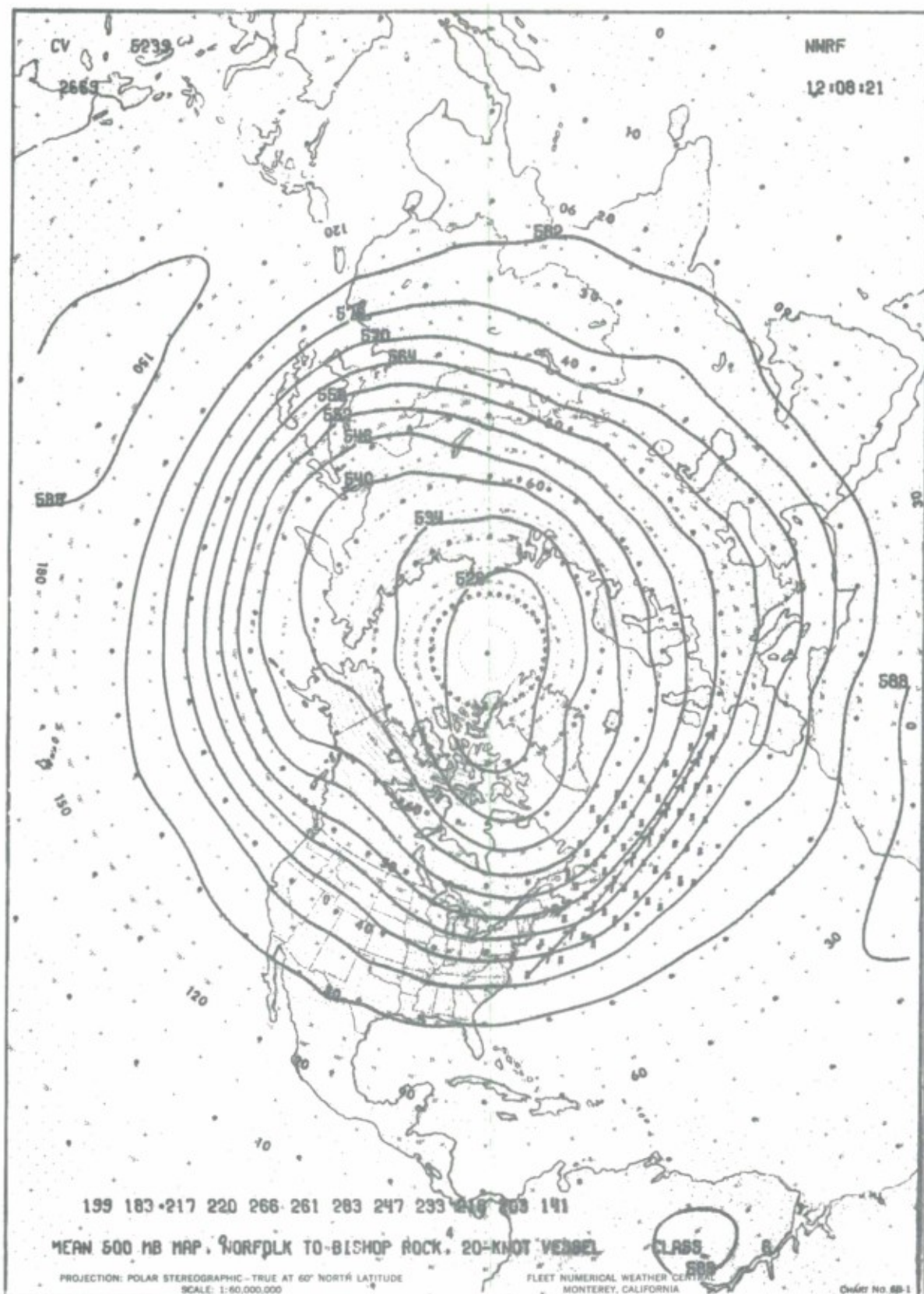


Figure F-5(b).

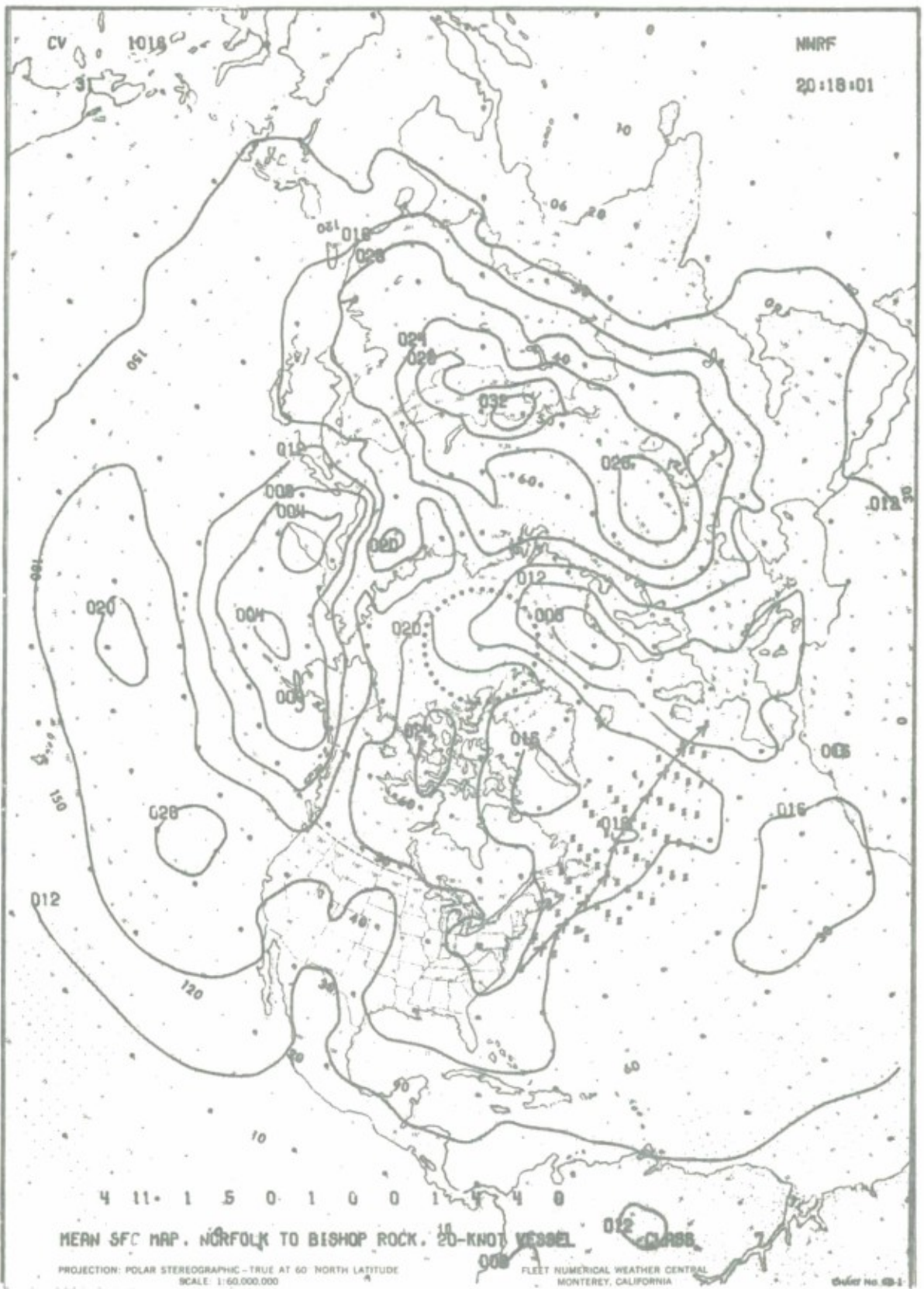


Figure F-6(a).

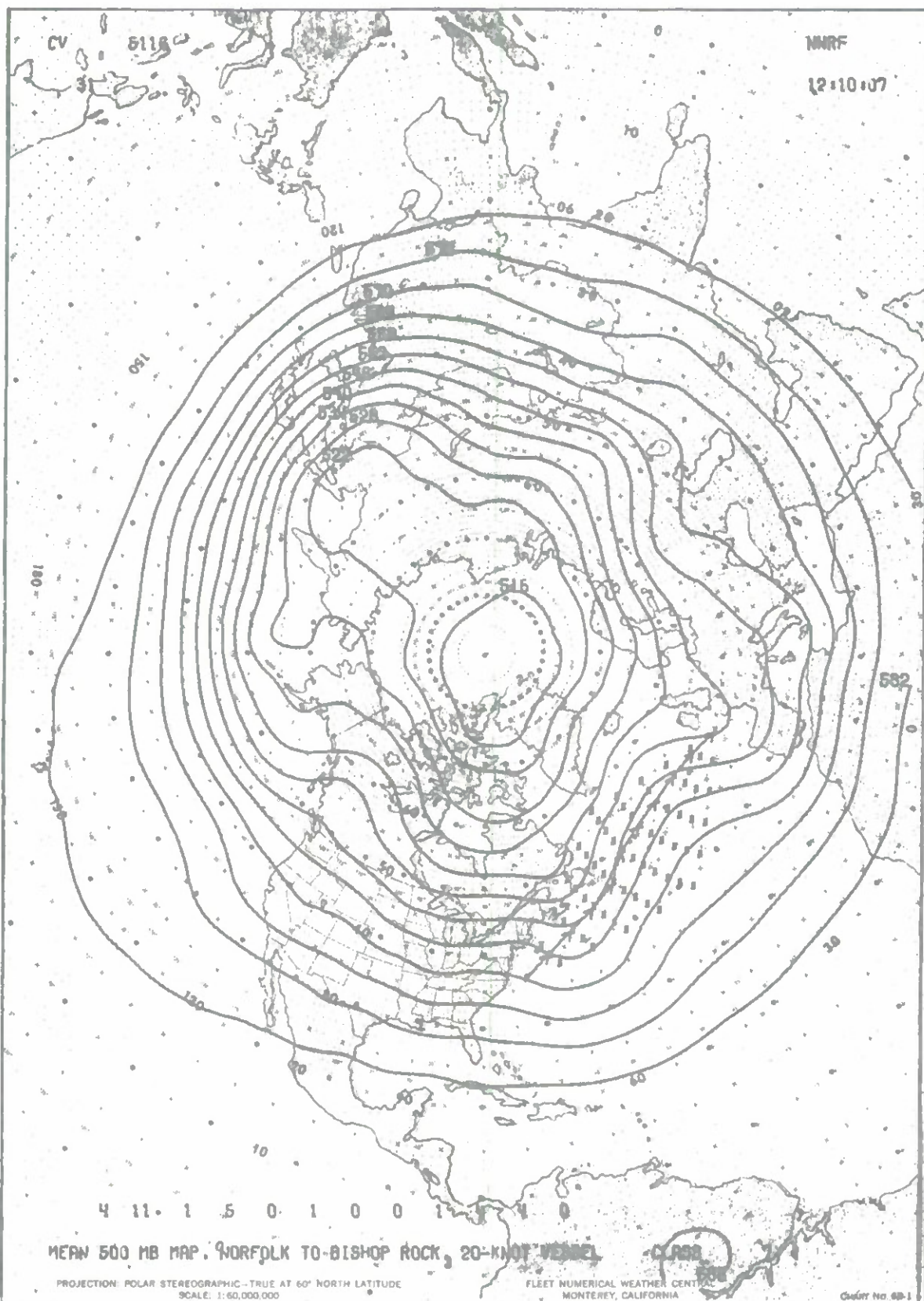


Figure F-6(b).

APPENDIX G

BISHOP ROCK TO NORFOLK

20-KNOT VESSEL

FIGURE G-1	Class 2
FIGURE G-2	Class 3
FIGURE G-3	Class 4
FIGURE G-4	Class 5
FIGURE G-5	Class 6
FIGURE G-6	Class 7
FIGURE G-7	Class 8
FIGURE G-8	Class 9
FIGURE G-9	Class 10

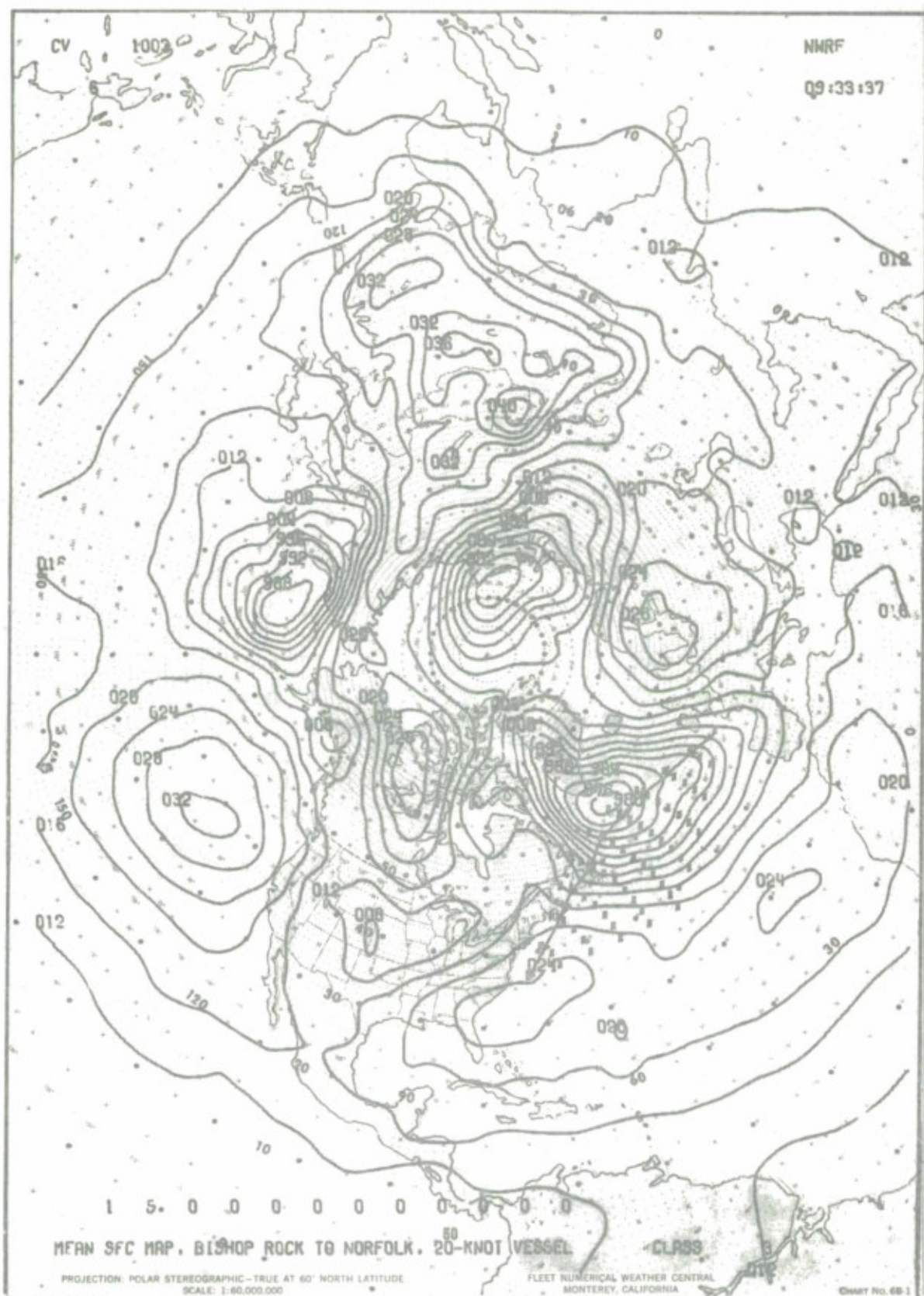


Figure G-2(a).

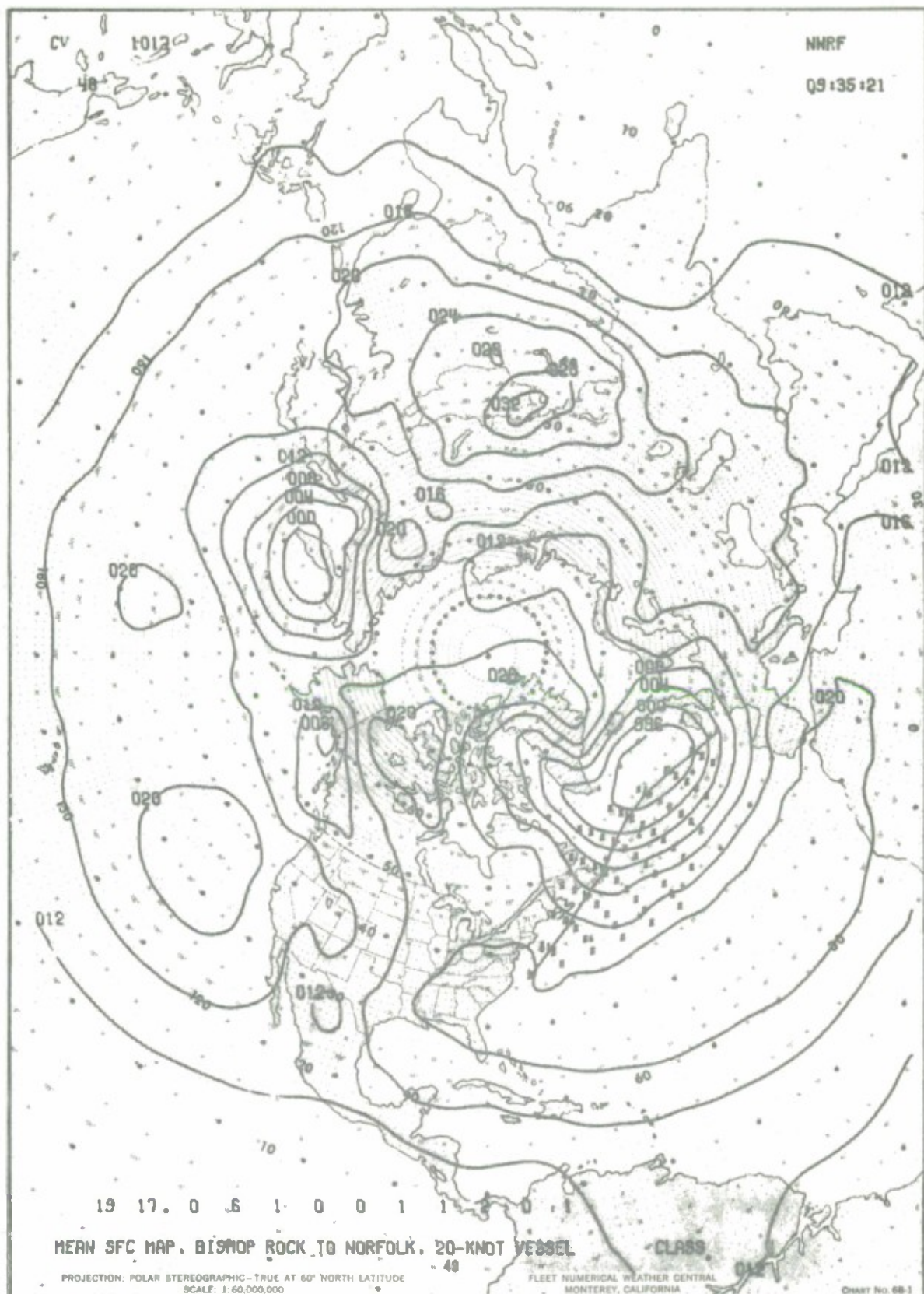


Figure G-3(a).

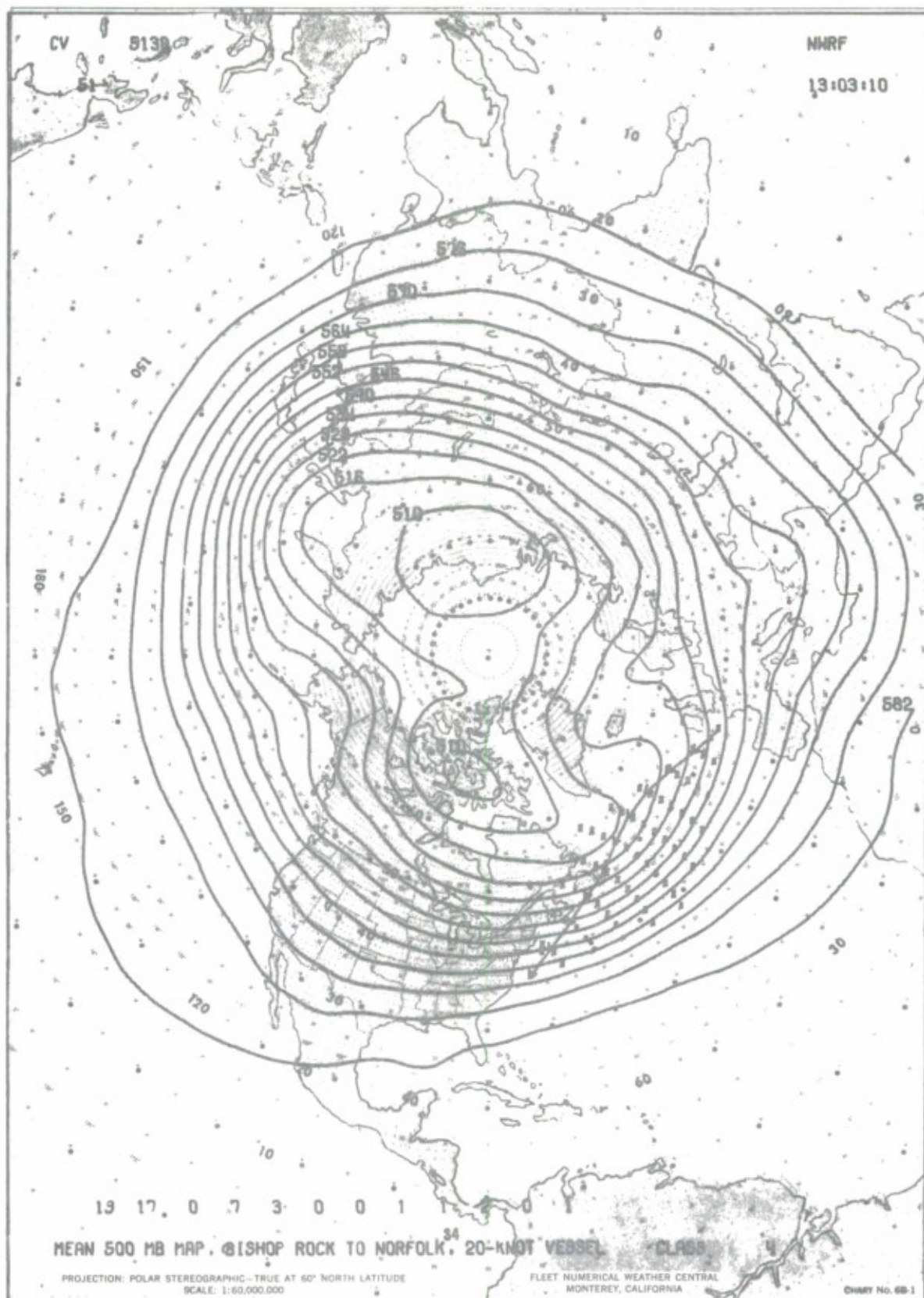


Figure G-3(b).

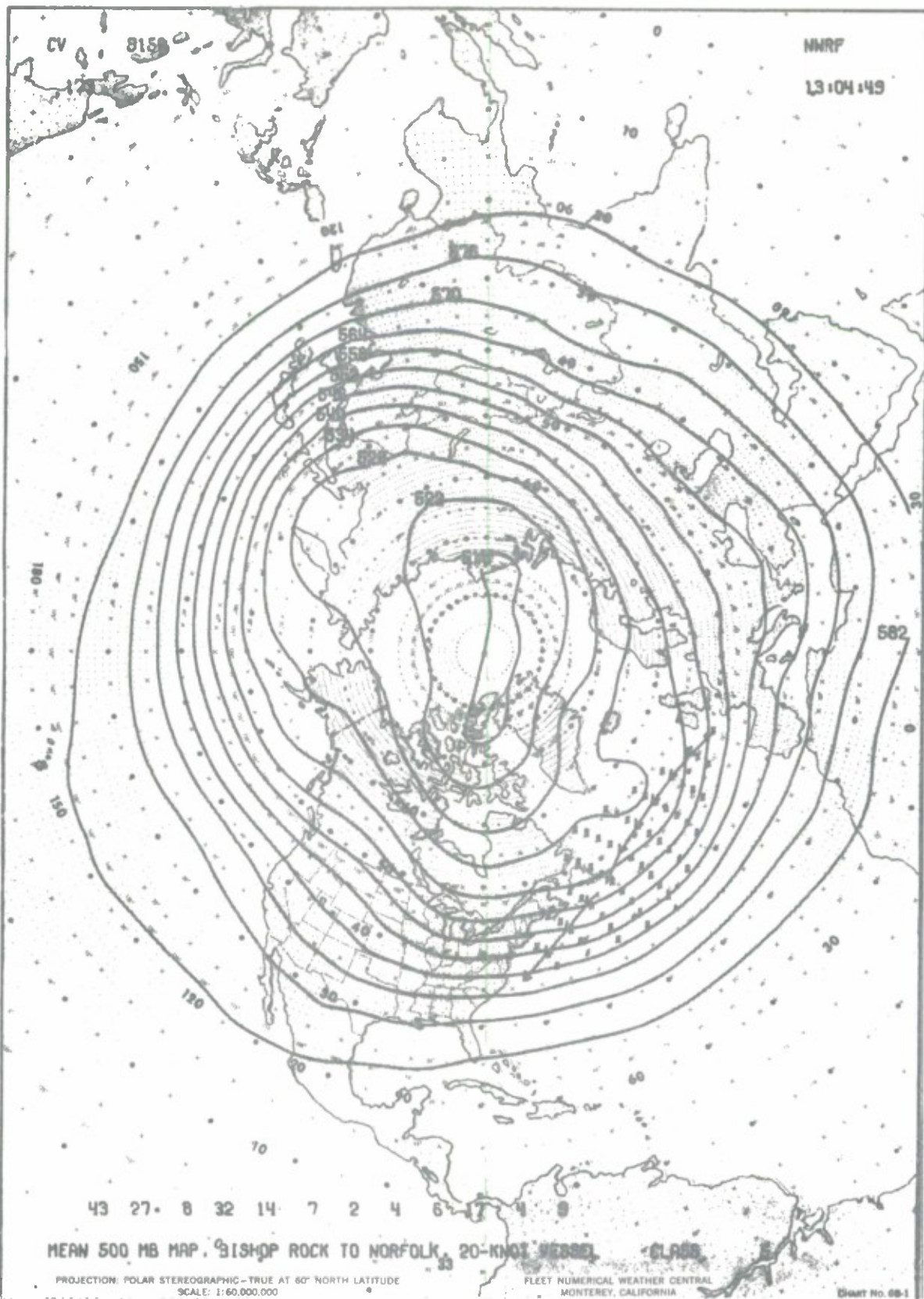


Figure G-4(b).

MEAN SFC MAP, BISHOP ROCK TO NORFOLK

20-KNOT VESSEL

CLASS 6

MISSING

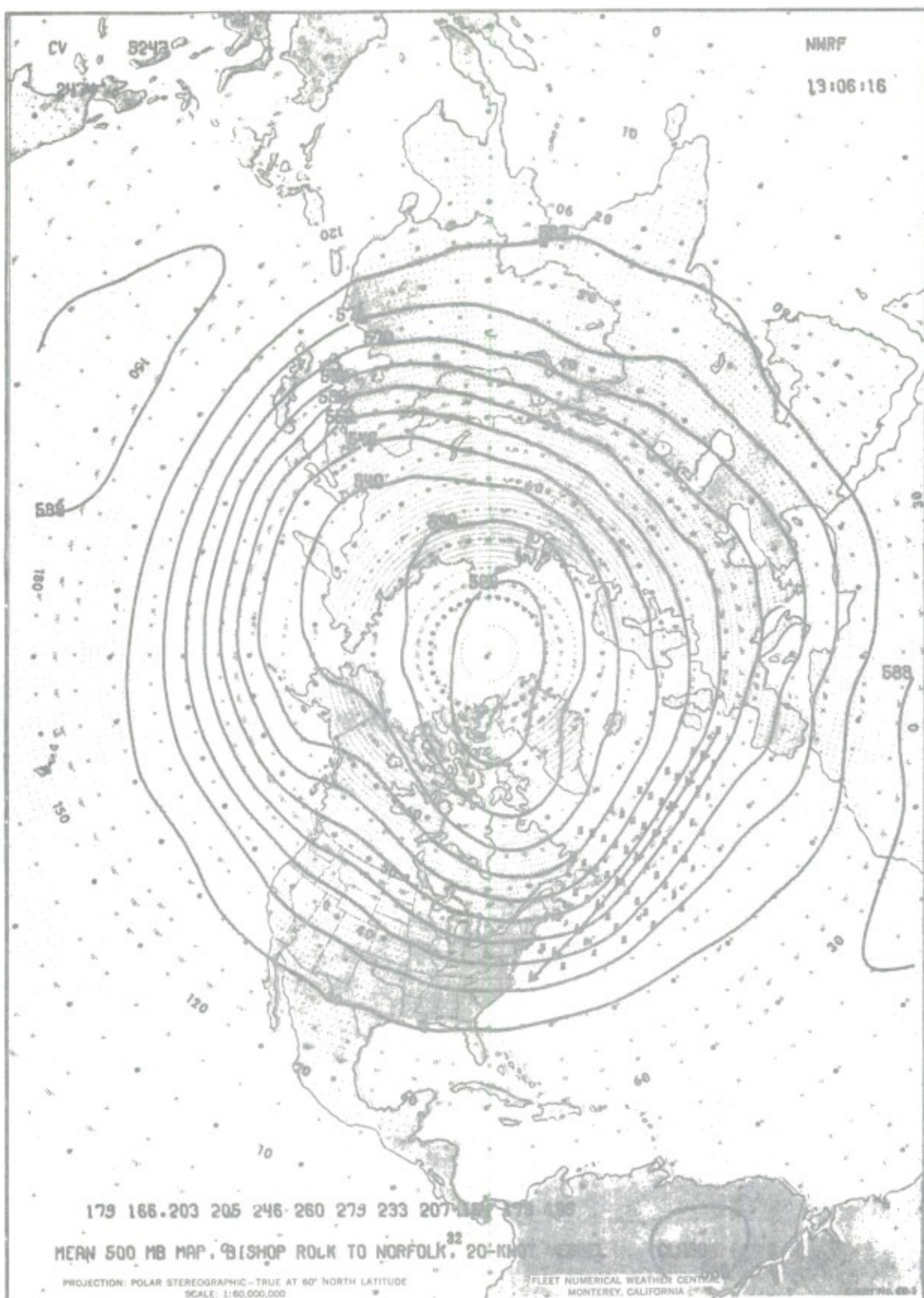


Figure G-5(b).

MEAN SFC MAP, BISHOP ROCK TO NORFOLK

20-KNOT VESSEL

CLASS 7

MISSING

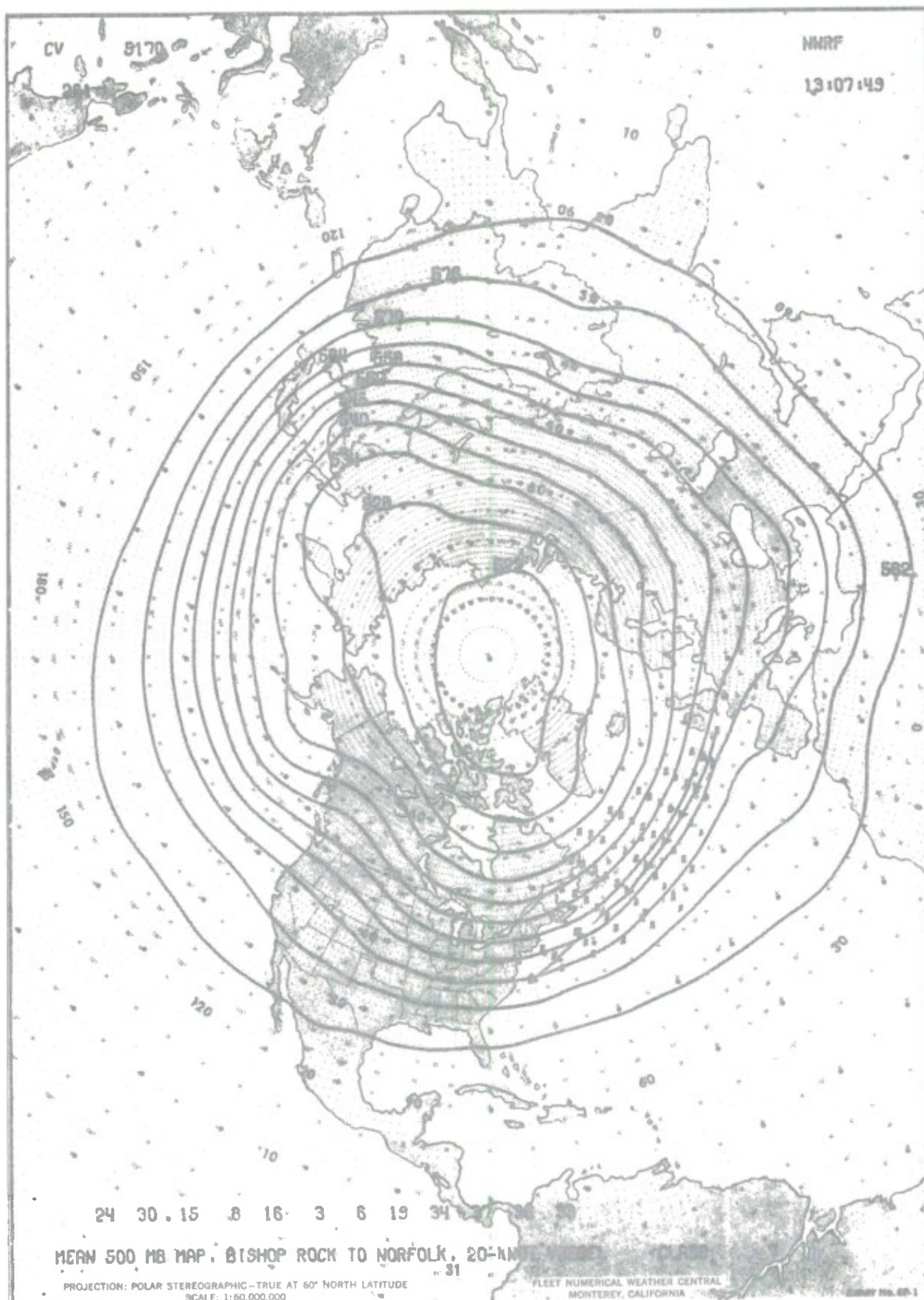


Figure G-6(b).

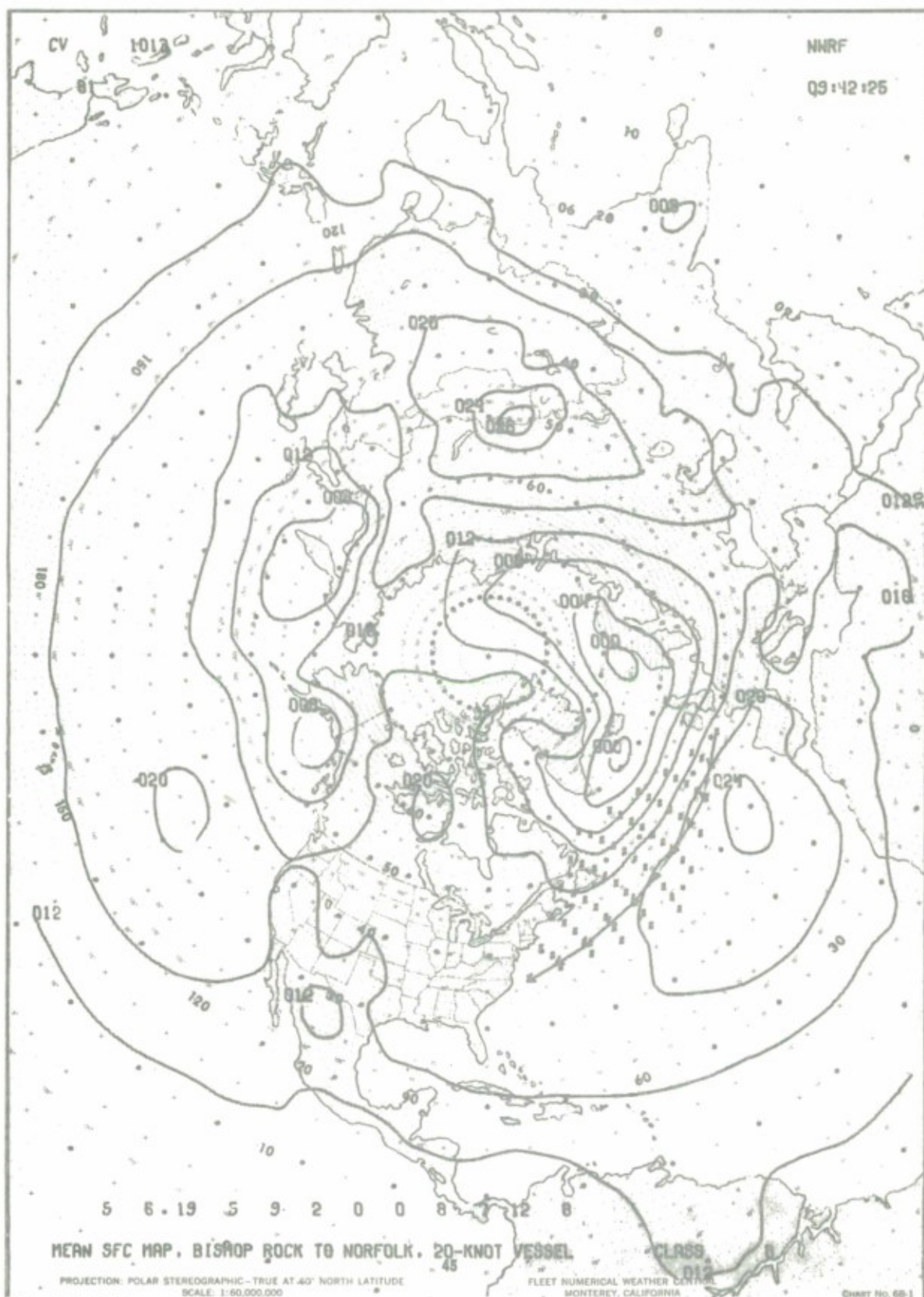


Figure G-7(a).

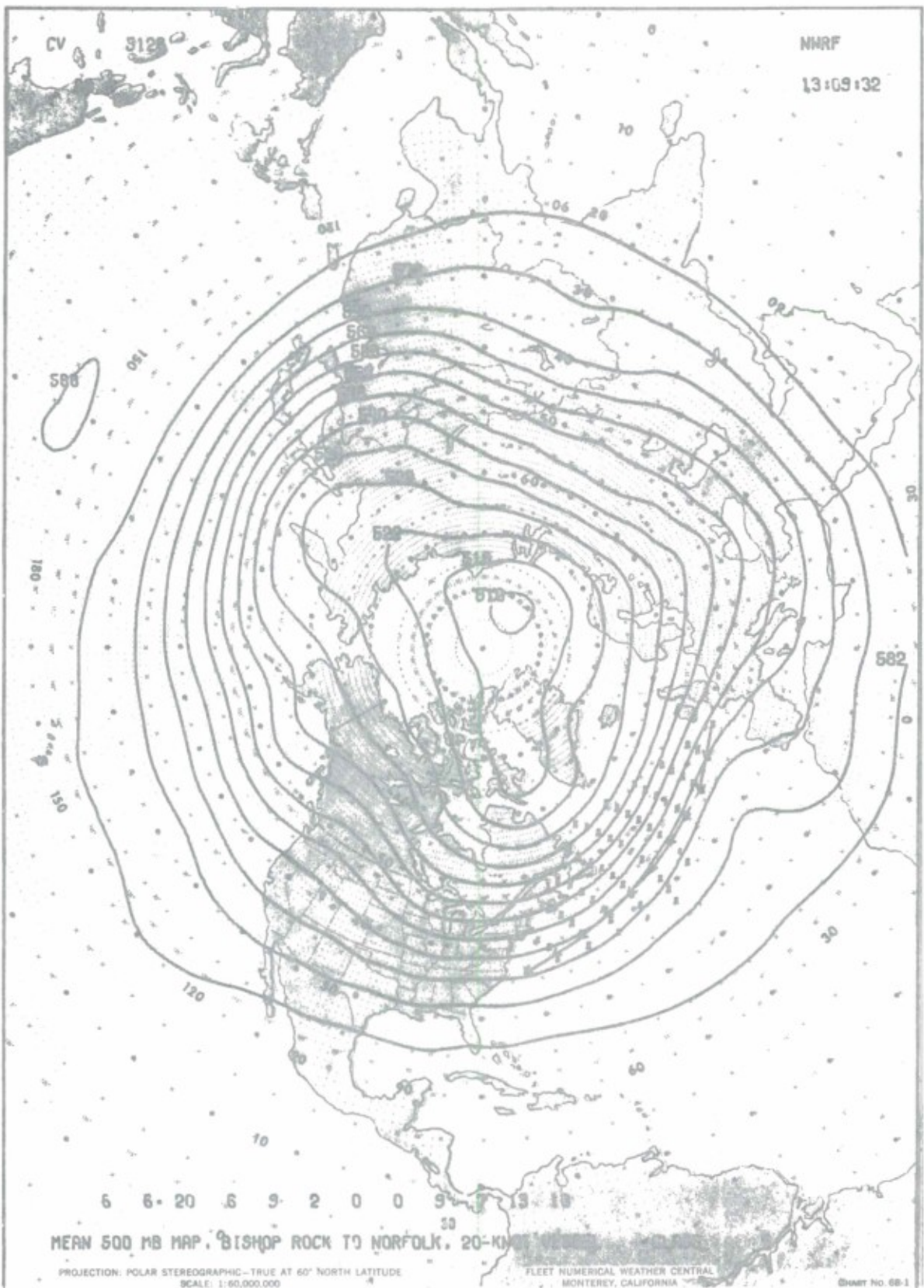


Figure G-7(b).

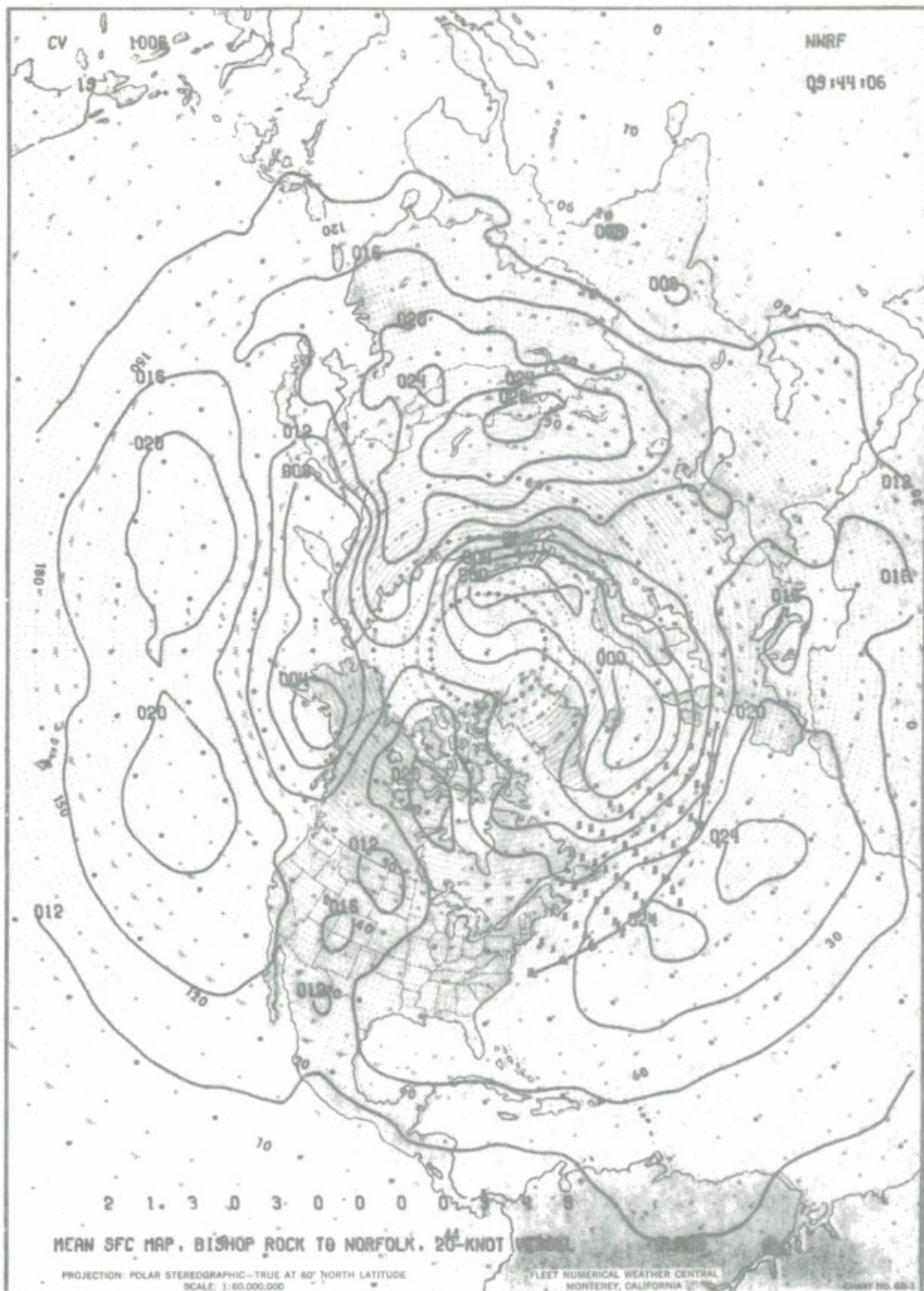
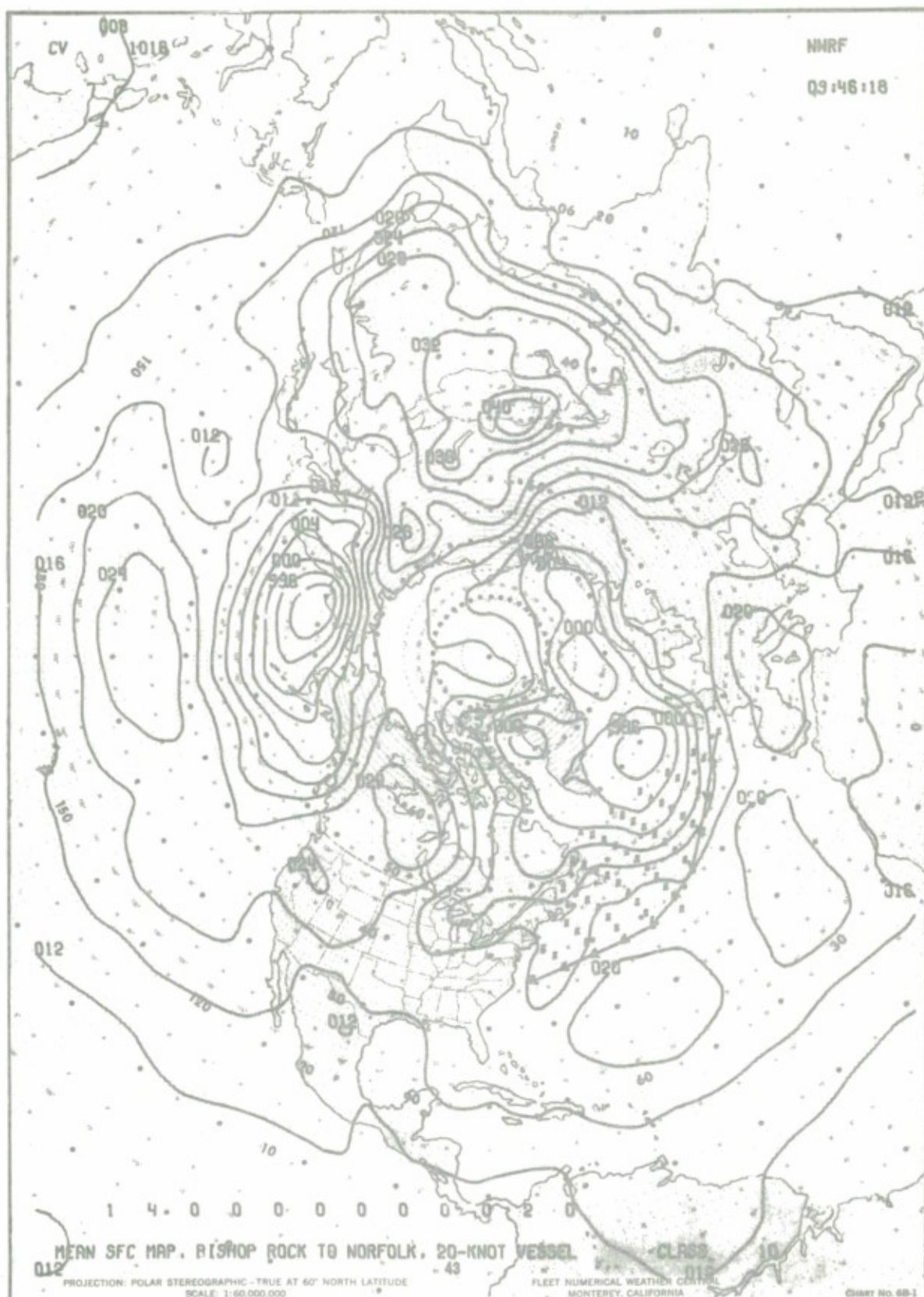


Figure G-8(a).



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Environmental Prediction Research Facility
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A Numerical Study in Optimum Track Ship Routing Climatology

Frederick W. Nagle

September 1972

174 169

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ENVPREDRSCHFAC
 Technical Paper No. 10-72

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Environmental Prediction Research
 Facility, Naval Postgraduate School
 Monterey, California 93940

A brief discussion of the background and history of optimum track ship routing is presented. The basic problems are formulated and the approach used in this investigation is described. The computing scheme is described graphically and textually.

The results of this investigation are presented in two forms: (1) computer-generated histograms showing mean time saved by month for various trans-Atlantic routes; and (2) computer-drawn charts of various routes, by class (described), plotted against 5-year surface and 500-mb means.

FORM 1473

(1 of 1)

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Optimum Track Ship Routing
 Climatology
 5-Year Surface Mean Charts
 5-Year 500-Mb Mean Charts
 Trans-Atlantic Routes
 Numerical Ship Routing